VENTILATION DESIGN HANDBOOK ON

Animal Research Facilities Using Static Microisolators

VOLUME 1 OF 2

NATIONAL INSTITUTES OF HEALTH
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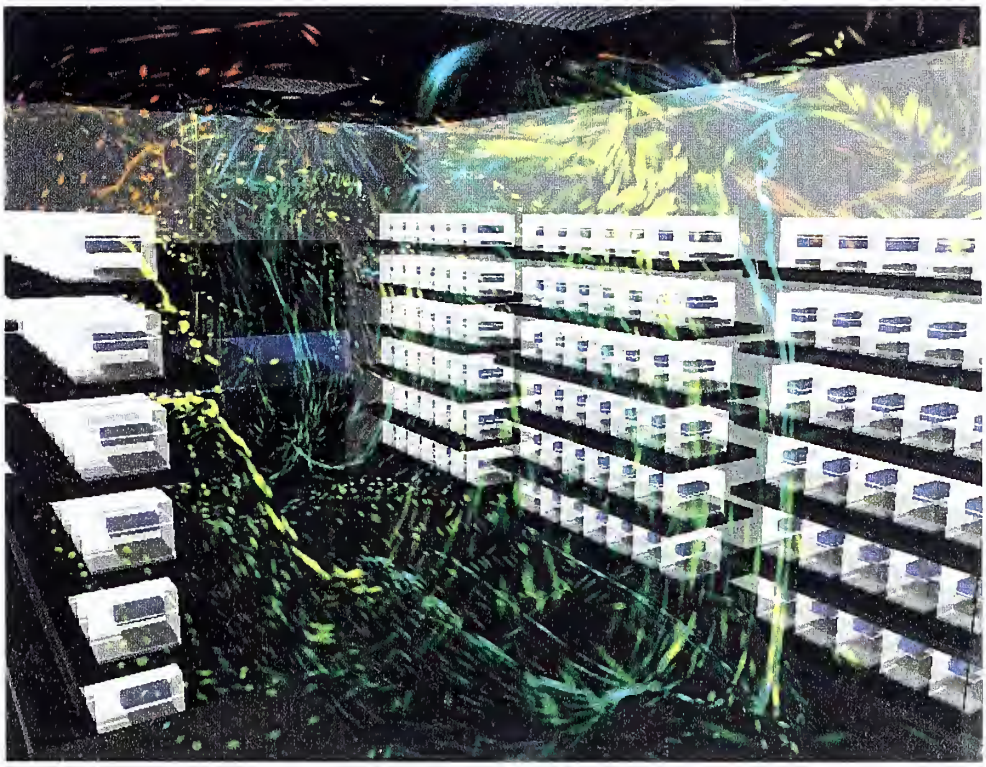
National Institutes of Health

Ventilation Design Handbook on Animal Research Facilities Using Static Microisolators

VOLUME I



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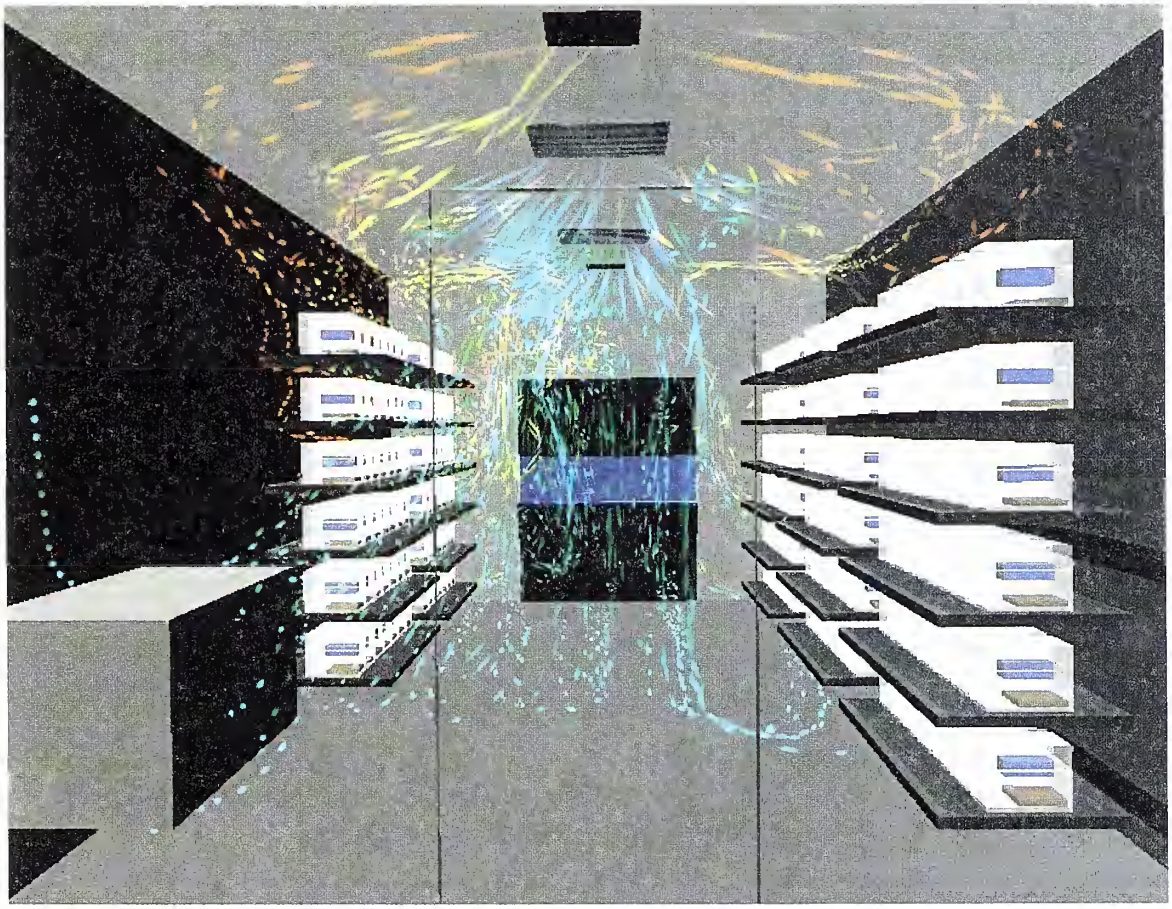

EXECUTIVE SUMMARY

Optimum air quality in laboratory animal facilities is essential for the general health and well-being of researchers, animal caregivers, and the animals, as well as for the integrity of the studies. Since both genetic heritage and the environment influence biological responses, researchers must always be aware of the influence of the environment on the animals' biological responses. With more information about environmental effects, laboratory animal facility design and management can be improved. Researchers will obtain the most reliable and repeatable results from their studies and experiments when laboratory animals have the best possible environmental conditions.

Many thousands of square feet of animal research facilities are designed and constructed each year. Unfortunately, inadequate information is available regarding ventilation rates and patterns that are required to maintain acceptable micro (cage) and macro (room) environments. There is an immediate need for a definitive scientific basis for selecting the ventilation rates and for designing effective ventilation systems for laboratory animal facilities. Engineers need this information to design environments with good air quality and low energy.

Current ventilation guidelines are based largely on anthropomorphic views and not on scientifically defined animal needs. Most research has focused solely on room conditions. Limited research has addressed ventilation rates, room air distribution, relative humidity and temperature, and other factors and interactions that contribute to acceptable and uniform environments for laboratory animals.

Laboratory animal ventilation should balance air quality, animal comfort, and energy efficiency to provide cage environments that optimize animal welfare and research results. Conditions that optimize animal welfare minimize unintended stress factors that can affect research results. Researchers and animal caregivers have the right to expect a healthy and pleasant working environment.

The literature review described in section 1.3 identifies the following important factors in controlling the macro- and microenvironments:

- Ventilation in filter top cages does not necessarily increase with increasing room ventilation air change rates
- The filter top can significantly affect cage ventilation performance
- Improved cage washing procedures and animal room cleanliness may reduce the concentrations of ammonia that produce bacteria
- Bedding type can significantly affect ammonia generation
- Ammonia concentration over 25 ppm promotes the infection in rats' respiratory tracts
- A recent study suggests that groups of five mice display a behavioral and autonomic thermoneutral zone that is surprisingly similar to individual mice. Individual and group-

housed mice prefer a temperature of approximately 29 to 30 °C (84 to 86 °F), which is warmer than the standard housing temperature of 22 to 24 °C (72 to 76 °F). This suggests that groups of mice may experience cold stress under standard housing conditions.

A comprehensive study of air movement, heat transfer, and contamination dispersal in the macro- and microenvironment in animal facilities could only be undertaken using computational fluid dynamics (CFD). CFD is an advanced three-dimensional mathematical technique used to compute the motion of air, water, or any other gas or liquid. All conditions must be correctly specified in the CFD simulation in order to obtain accurate results.

All the inputs for the CFD had to be defined for this study, including heat dissipation and surface temperature of the mice; and moisture, CO_2, and NH_3 generation rates for mice. Defining this data required an extensive series of experimental measurements using sets of outbred female mice (HSD-ICR) with an initial age of four weeks. The mice were placed in microisolator cages with hardwood (beta chip) shaving bedding for a 13-day period. In addition to providing specific data and recommendations this document details experimental and numerical procedures that can be used for other species.

Cage characteristics needed to be fully understood so an accurate mathematical model of a microisolator cage could be built. As most of these data were not available from literature, an unprecedented set of experimental measurements was undertaken. Without this foundation of accurate experimental data the CFD analysis of the rooms would have had limited value.

On the subject of ventilation the most commonly accepted source of performance criteria for research animal facility ventilation systems is the *Guide for the Care and Use of Laboratory Animals*, Institute of Laboratory Animal Resources (1996) and the *American Society of Heating Refrigerating and Air Conditioning Engineers Applications and Fundamentals Handbooks*. The *Guide* makes general recommendations for ventilation of animal facilities and recognizes that investigation of individual designs by techniques such as CFD may be necessary to ensure optimum performance, e.g. "The guideline of 10-15 fresh-air changes per hour has been used for secondary enclosures for many years and is considered an acceptable general standard. Although it is effective in many settings, the guideline does not take into account the range of possible heat loads; the species, size, and number of animals involved; the type of bedding or frequency of cage-changing; the room dimensions; or the efficiency of air distribution from the secondary to the primary enclosure. In some situations, the use of such a broad guideline might pose a problem by overventilating a secondary enclosure that contains few animals and thereby wasting energy or by underventilating a secondary enclosure that contains many animals and thereby allowing heat and odour accumulation."

Ventilation recommendations are often based on room air exchanges. However, cage ventilation rates may be inadequate in some cages and excessive in others depending on cage and facility design. Recommendations for room ventilation rates of 10 to 15 air changes per hour (ACH) are an attempt to provide adequate ventilation for the room and the cages. This recommendation is based on the assumption that adequate ventilation in the macroenvironment provides sufficient

ventilation to the microenvironment. This may be a reasonable assumption when cages have a top of wire rods or mesh. However, several studies have shown that covering cages with filter tops provides a protective barrier for rodents and reduces airborne infections and diseases, especially neonatal diarrhea, but can result in significant differences in microenvironmental conditions due to changes in air movement caused by the cage cover.

Exactly how well or how poorly these filter top cages are ventilated in a room was not known until this research was completed. Previously published literature only identifies the relative performance of different types of tops. Although some data exist on the flow resistance of filter material, determining how and how much air gets in and out of the cages was vital for this study. This research has quantitatively measured the ventilation performance of a specific filter top microisolator cage for different airflow conditions. It investigated the airflow between the upper and lower moldings, taking into consideration leakage that occurs due to the fact that the top sits loosely on the bottom, compared with the ventilation through the filter top itself. A wind tunnel was designed and tests were performed to compare the ventilation of single cages to two cages standing next to one another, closely representing a cage sitting on a rack in an animal facility room. CFD models of a cage in the wind tunnel, various orientations of a cage in the wind tunnel, and airflow velocities were constructed and run. These showed an excellent agreement between the simulation results and the measured values, confirming that the cage model used in the room simulations was representative of a microisolator cage.

In order to analyze the ventilation performance of different laboratory animal research facilities, numerical methods based on computational fluid dynamics were used to create computer simulations of more than 100 different room configurations. The performance of this approach was successfully verified by comparison with experimental measurements in a typical laboratory. A total of 12.9 million experimental data values were collected in an empty (except for the ventilation system) laboratory scenario, while 0.66 million data values were collected in a populated (included simulated animal racks) laboratory. The comparison between the numerical and experimental data was particularly good for temperature and gas concentrations. In particular, the average error between the experimental and computational temperature in the laboratory was 14.36 percent, while the equivalent value for gas concentrations was 14.50 percent. The low air velocities proved more difficult to measure, which further demonstrated the need for computational techniques that are not limited by measurement uncertainties encountered at low velocities. To investigate the relationships between room configuration parameters and the room and cage environments within laboratory animal research facilities, the following parameters were varied:

- Supply air diffuser type and orientation, and air temperature and moisture content;
- Room ventilation rate;
- Exhaust location and number;
- Room pressurization;
- Rack layout and cage density;
- Change station location, design, and status;

- Leakage between the lower and upper cage moldings; and
- Room width.

The 100 different room configurations were then ranked according to various parameters, namely:

- Room Temperature;
- Cage Temperature;
- Room Relative Humidity;
- Cage Relative Humidity;
- Room CO2;
- Cage CO2;
- Room NH3;
- Cage NH3.

It is therefore possible for the designer, in using this document, to select the most appropriate design configuration based on their particular requirements.

Room pressurization, change station design, and room width were found to have little effect on ventilation performance. However, all the other factors were found to affect either or both of the macro- or microenvironments to a greater or lesser extent.

The key conclusions of this research are:

- Ammonia production rates depended on the relative humidity in the cages and the number of days that had elapsed since the bedding was changed. Figure 0.1 shows the data points measured and the best fit lines ("Poly.") for the data. Five days after the last change of bedding ammonia was produced in a high humidity environment at approximately three times the rate as in a low humidity environment. This research showed that the rate of ammonia generation was not directly dependent on temperature, although temperature has a direct effect on the relative humidity of the air.

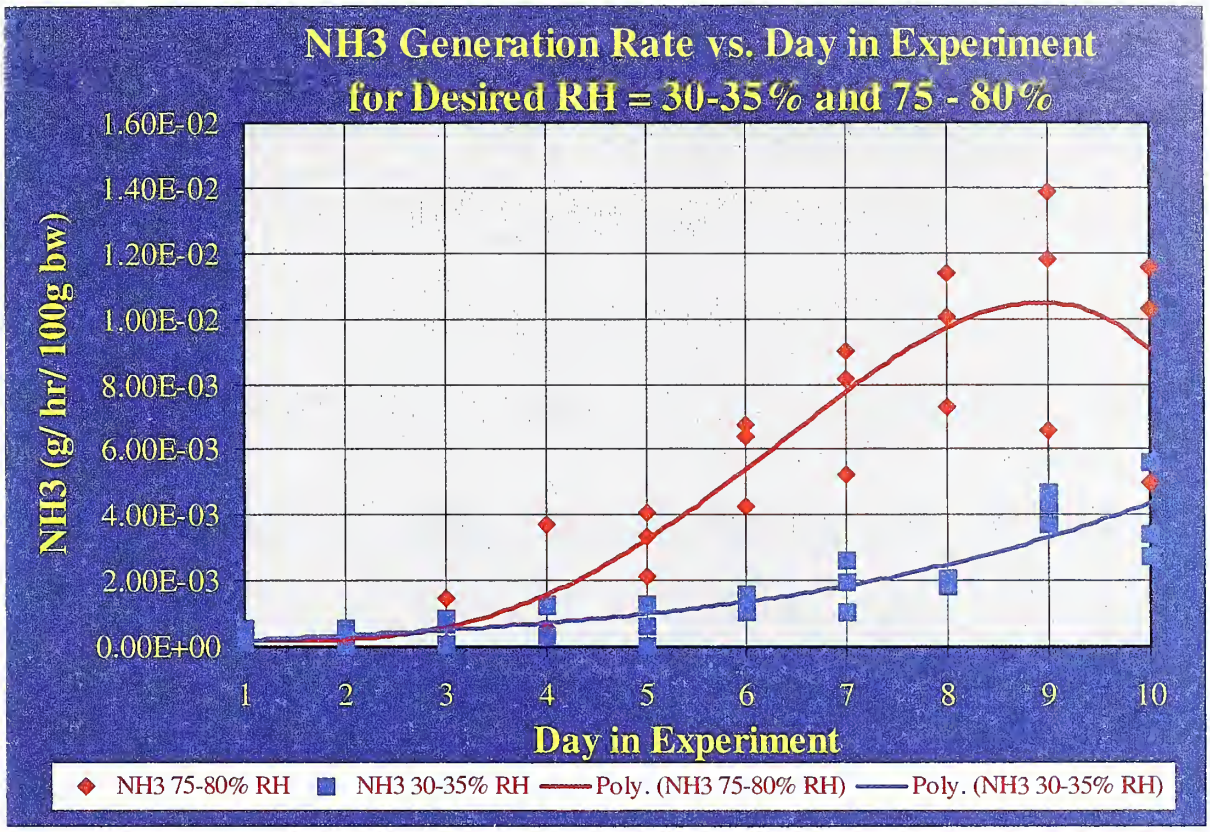

***Figure 0.1**. Ammonia generation rate measured over 10 days at high and low humidity*

- Acceptable room and cage ammonia concentrations after five days without changing cage bedding are produced by room supply airflow rates of about 0.85cfm (0.0004m^3/s) per 100g of body weight of mice. This is equivalent to 5 ACH for rooms with single density racks that were considered in this study, and 10 ACH for rooms with double density racks. This indicates that it could be possible to adjust the common practice of changing bedding every four days to changing after five days.

  The temperature of the supply air must be set appropriately for the heat load in the room. In this study, the change station produced 720W and the mice around 500W in the single density racks, which required supply discharge temperatures of 11 °C (52 °F) at 5 ACH to provide exhaust temperatures of around 22 °C (72 °F). For double density racks the supply discharge temperature should be 14.8 °C (59 °F) at 10 ACH.

  This study used dark period/lights off to give the highest CO_2 and NH_3 generation rates. If lighting is to be included an allowance should be made for 600W of additional heat from the lights leading to lower supply discharge temperatures.

- Increasing the room ventilation rate for a given design appears to have a beneficial effect on the room's breathing zone ventilation as measured by CO_2 and ammonia concentrations (see figure 0.2). For the single density racks parallel to the walls increasing the supply flow rate from 5 ACH to 20 ACH reduced the breathing zone CO_2 concentration from 140 ppm to 63 ppm. This is a decrease of 55 percent. For the double density racks perpendicular to the walls the reduction is even more dramatic. A reduction of over 70 percent, from over 300 ppm to 93 ppm, occurred when the flow rate was increased from 5 ACH to 20 ACH.

  However the high values of CO_2 concentration of about 300 ppm above the background levels are still significantly too low. American Conference of Governmental Industrial Hygienists (ACGIH) recommends a threshold limit value (TLV), time weighted average (TWA) of 5,000 ppm (9,000 mg/m^3) for carbon dioxide. ACGIH also recommended a Short Term Exposure Limit (STEL) of 30,000 ppm (5,4000 mg/m^3).

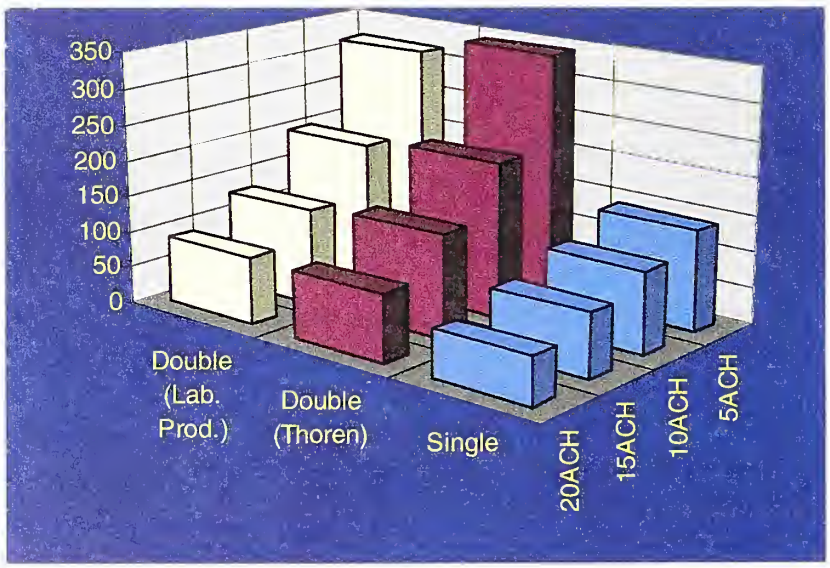

Figure 0.2 *Room Breathing Zone CO_2 concentrations (ppm) for single density racks with the Thoren change station and double density racks with both Thoren and Laboratory Products change stations*

Although 20 ACH appears to produce the best ventilation for the low induction diffuser with low level exhaust cases compared with over 50 percent of the 15 ACH runs, other diffusers, exhaust locations or rack layouts actually have even lower room CO_2 concentrations.

Higher supply discharge airflow rates are usually accompanied by higher supply discharge temperatures since the air does not have to be so cold to extract the heat generated in the room. This allows animal facility designers/operators to choose between using low supply volumes at lower supply temperatures, with a lower cost for fans but higher cost for air conditioning, or high flow rates at higher temperatures, which result in higher fan but lower

air conditioning costs. Which of these options will provide the best economic return depends on the facility's circumstances.

- Increasing the room ventilation rate does not have a significant effect on cage ventilation (see figure 0.3). Increasing the supply flow rate from 5 ACH to 20 ACH for single density racks parallel to the walls reduces the CO_2 concentration from 1764 ppm to 1667 ppm, a reduction of only 6 percent. For the double density racks perpendicular to the walls the reduction is slightly more significant: about 2300 ppm to 1800 ppm, or roughly 20 percent.

  Since air exchange rates in excess of 10 ACH do not materially improve environmental conditions within the cages, more care should be given to proper cage arrangement and air distribution.

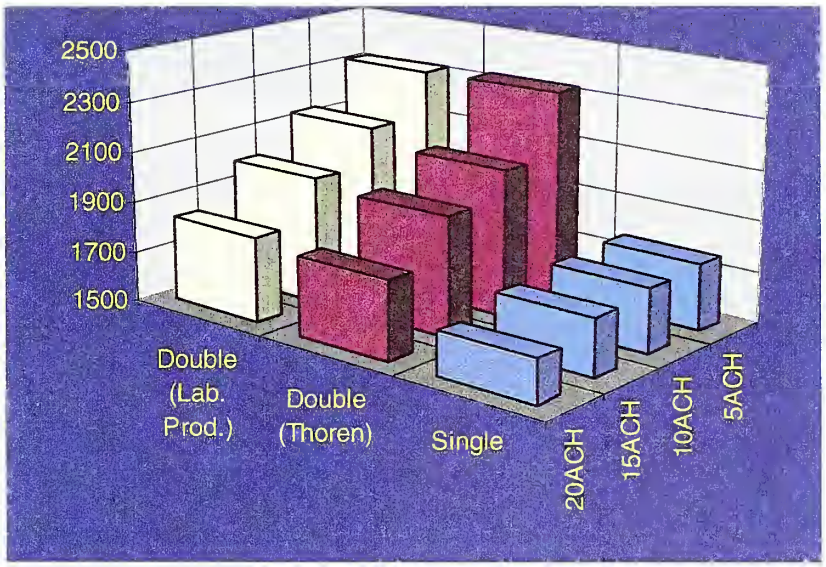

Figure 0.3 *Cage CO_2 concentrations (ppm) for single density racks with the Thoren change station and double density racks with both Thoren and Laboratory Products change stations.*

- Ammonia concentrations in both cages and rooms can be reduced by increasing the supply air temperatures. This reduces the relative humidity (RH), for a constant moisture content in the air. In addition, the lower RH leads to lower ammonia generation. Raising the supply discharge temperature from 18.8 °C (66 °F) to 22 °C (72 °F) at 15 ACH raises the room temperature by 3 °C (5 °F) to about 23 °C (73 °F), and the cages by 2.7 °C (4 °F) to around 24.8 °C (77 °F). This can reduce ammonia concentrations by up to 50 percent.

  Using 22 °C (72 °F) as the supply discharge temperature at 5 ACH, which is the lowest flow rate considered, for double density racks produces a room temperature of about 26 °C (79 °F) with cage temperatures only slightly higher. Although this higher temperature provides a

more comfortable environment for the mice (Gordon, Becker, and Ali, 1997) the high room temperature may be uncomfortable for the scientists and animal caregivers working in the room.

- Ceiling or high-level exhausts tend to produce lower room temperatures when compared to low-level exhausts. All CFD models were designed to have 22 °C (72 °F) for a given supply air temperature at the room exhausts. There were also a small number of tests run with high supply temperatures. These studies indicate that low-level exhausts are less efficient at cooling the room and will be more expensive to operate.

- Low-level exhausts appear to ventilate the cages slightly better than ceiling or high-level exhausts when the cages are placed parallel to the walls. Improvement was up to 27 percent for the radial diffuser, 4 percent for the slot diffuser, and 25 percent for the low induction diffuser. See figure 0.4. The ammonia concentration in the cages (see figure 0.5) appears to be even further reduced although this is due to the higher temperatures in the low-level exhaust cases when compared to the ceiling and high-level exhausts which act to reduce the relative humidity and the ammonia generation rate.

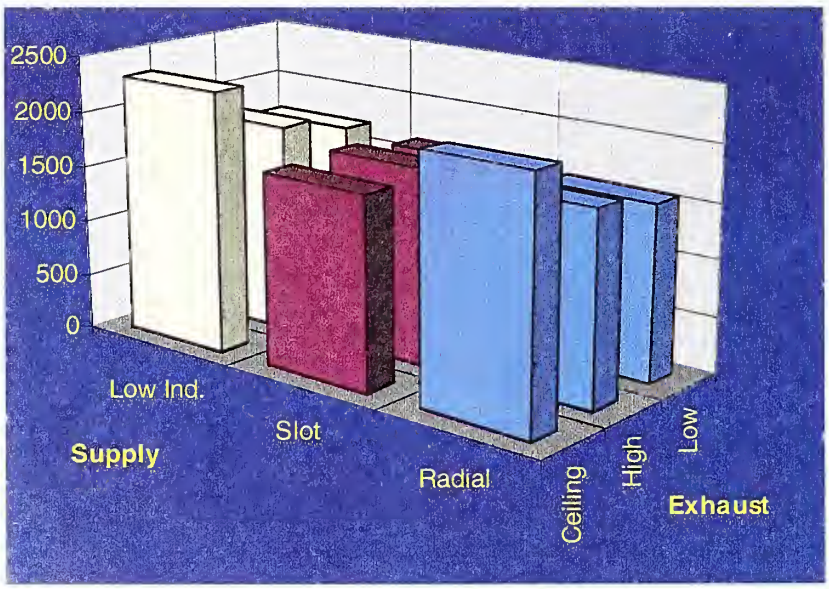

Figure 0.4 *Mean CO_2 concentration (ppm) in cages for Radial, Slot and Low Induction supply diffusers with Ceiling, High-Level and Low-Level Exhausts*

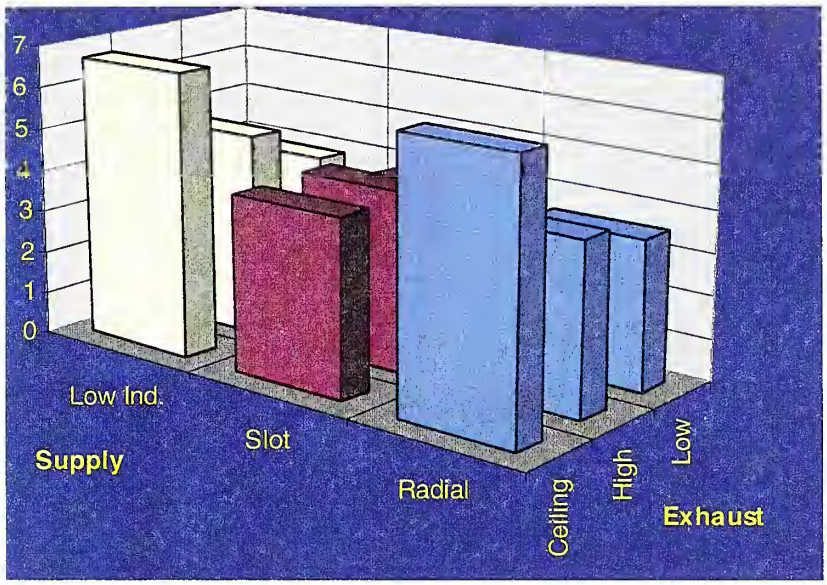

Figure 0.5 *Day 4 mean ammonia concentration (ppm) in cages for Radial, Slot and Low Induction supply diffusers with Ceiling, High-Level and Low-Level Exhausts*

The room concentrations of CO_2 and ammonia do not show any supply or exhaust type to be significantly better or worse than any other type (see figures 0.6 and 0.7). Of the many supply diffuser and exhaust locations considered in this work, it is not possible to select one configuration which will always perform better than another. Designers and operators of animal facilities will need to consider carefully which parameters are important to them and select a layout which balances all their requirements for animals and the humans that work with them.

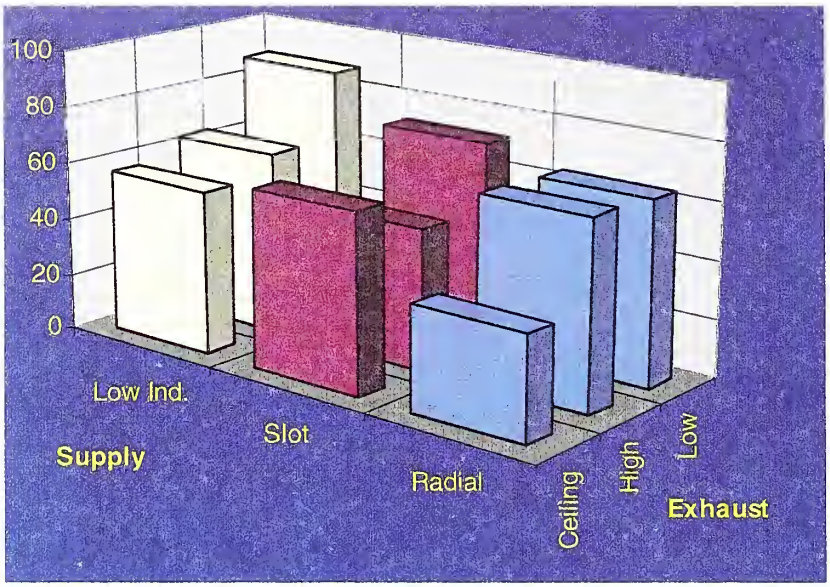

Figure 0.6 *Mean CO_2 concentration (ppm) in room breathing zone for Radial, Slot and Low Induction supply diffusers with Ceiling, High-Level and Low-Level Exhausts*

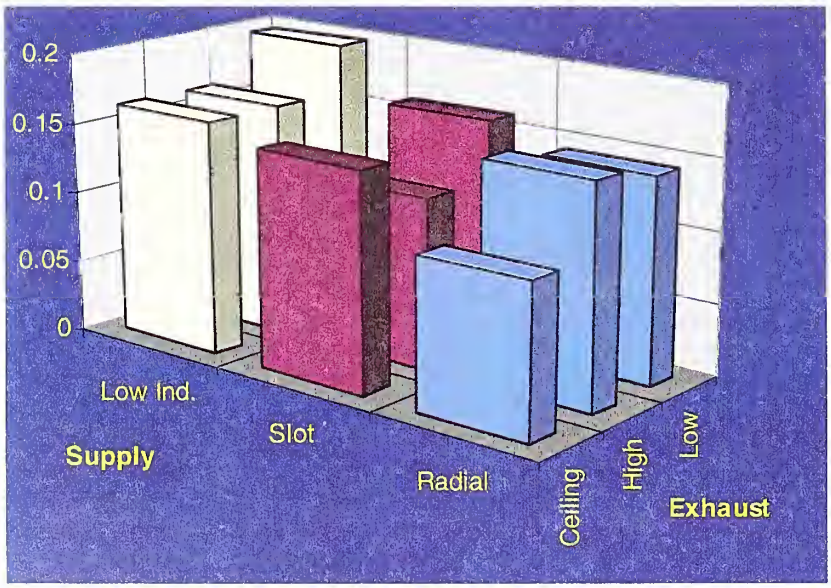

Figure 0.7 *Mean Day 4 ammonia concentration (ppm) in room breathing zone for Radial, Slot and Low Induction supply diffusers with Ceiling, High-Level and Low-Level Exhausts*

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FOREWORD

Laboratory animal ventilation should balance air quality, animal comfort, and energy efficiency to provide cage environments that optimize animal welfare and research efficiency. Conditions that optimize animal welfare automatically tend to improve research efficiency because it is especially important in research to minimize unintended stress factors. Additionally, the laboratory animal ventilation system should provide a healthy and pleasant environment for researchers and animal caregivers.

This work examines the relationship between the air quality in the macro- (room) and micro- (cage) environments in animal facilities. It provides the first systematic study of the ventilation of the macro- and microenvironments simultaneously. It demonstrates only a weak link between the room ventilation and the conditions inside the microisolator cages. Further, it shows that improvements in the room conditions may harm cage ventilation. For example, low level exhausts can produce 27 percent lower CO_2 concentrations in cages while raising it to over 70 percent in rooms.

In order to carry out the research, extensive experimental data was collected to provide an accurate basis for the behavior of mice in terms of heat, carbon dioxide, and ammonia production. They are necessary inputs to the computational fluid dynamics (CFD) simulations. In addition to providing specific data for a particular strain of mouse and a type of bedding, this document details measurements and parameters for experimental procedures that can be used for other species as well.

It was also necessary to carry out numerous measurements to calibrate the CFD model of the cage, particularly to evaluate the resistance of the filter material in the lid of the cage as well as to estimate the effects of any leakage where the bonnet top of the cage sits on the bottom of the cage. It was found that a significant amount of air did flow under the lips of the cages in the wind tunnel tests. The CFD model was modified to account for this. Without the experimental data it would have been impossible to carry out the CFD simulations with any confidence that the model of the cage really represented a typical microisolator cage.

There was also some experimental work done to measure airflow in both empty and occupied rooms with racks of cages containing "dummy" mice that provided both heat and CO_2 gas. Unfortunately, the low velocities present in the test rooms made accurate measurement very difficult. The comparison between CFD and measurement did not meet our expectations, particularly for the empty room, which was further complicated by temperature variations in an apparently isothermal situation.

While this document does not define a perfect animal facility it does demonstrate how given options can be chosen to influence the room and the cage. The results form a database of performance data for different configurations to which proposed designs can be compared.

The research proved that raising the supply temperature, which lowers the relative humidity, not only reduces ammonia production but provides conditions closer to the thermoneutral zone for mice. Analyzed supply temperatures of about 22 °C (72 °F) were found to result in room temperatures between 24 and 26 °C (75 to 79 °F) with cages around 2 °C (4 °F) higher. While this is within the preferred temperature range for mice, it may prove too warm for scientists.

Why You Should Read and Refer to this Document

A number of recent facilities have been built with high level exhaust systems. This happened as a result of publications that reported on studies that concentrated on the thermal ventilation efficiency of the macroenvironment. Those studies ignored the internal cage microenvironment. When the exhaust is placed at high level, it is easy to overlook the reduced cage ventilation efficiency for filter top cages. Designers, facility managers, and veterinarians should therefore refer to this document when they need to make an informed decision on the choice of exhaust location.

This document also provides valuable information about ventilation rate per 100g of stock and its relationship with bedding change frequency. Furthermore the research indicates our ability to reduce ammonia generation by raising temperatures. This may have energy efficiency benefits for rooms operating largely or exclusively on cooling, although consideration must be given to the relative humidity in those situations.

How To Use This Document

The document is in two volumes. Volume I describes the project and its findings, appendix I in volume I presents relevant experimental data, such as experimental and calibration procedures and tabulated experimental data, and volume II presents summary data for more than 100 animal research facility configurations.

Volume I is divided into eight major sections:

1. Introduction	5. Computational Fluid Dynamics Section
2. Animal Room Variations	6. Statistical Analysis
3. Evaluation of Results and Recommendations	7. Glossary of Relevant Terms
4. Establishing and Verifying the CFD Methodology	8. References

Section I: Provides background information that will aid in understanding the project objectives and scope. This should be read by all.

Section II: Outlines the computational fluid dynamics (CFD) base line model, including such details as the physical geometry chosen, details of cages, racks, and change stations. This section also includes a table summarizing the description of 100 animal research facilities considered in this project. It outlines the different means of presenting the vast data generated. It offers explanations of a qualitative approach to visualizing the flow (vector plots, fill plots) and of the quantitative analysis parameters such as mean temperatures, CO_2 and NH_3 concentrations in the in the room and cage breathing zones. The results from the base line simulation are presented using these two approaches.

Section III: Gives a graphical presentation of results for all 100 animal research facilities for mean room breathing zone temperature, mean cage temperature, mean room breathing zone relative humidity, mean cage relative humidity, room breathing zone CO_2 concentration, and mean cage CO_2 concentration. It also presents room breathing zone and mean cage NH_3 concentrations on a given day within the 10-day cycle (day 4). The section includes conclusions and recommendations for the following: supply type and exhaust position; air change rate; change station design and status; pressurization of room relative to corridor; orientation of cage racks and rack groupings; density of cages; side cracks of cages sealed instead of open; room width; and supply temperature. Finally, this section presents NH_3 levels in the cages and breathing zone for all the 100 animal research facilities over the 10 days of the cycle.

Section IV: Contains experimental data and validation of the computational fluid dynamics methodology used in this project. This section identifies and explains the experimental tests and procedures for the cage conditions, CO_2, NH_3, H_2O, and heat generation for mice. In this section the validation of CFD vs. experimental work as well as diffuser validation against manufacturer's data are presented.

Section V: Provides an explanation of the methodology used. It provides a basis for those with no knowledge of computational fluid dynamics. Includes description of Navier-Stokes equations and boundary conditions used in this project.

Section VI: Describes a statistics overview and analysis of variance (ANOVA) techniques used for this project. ANOVA is a broad range of analytic techniques that address questions of statistical significance through calculation methods that divide overall variance into components.

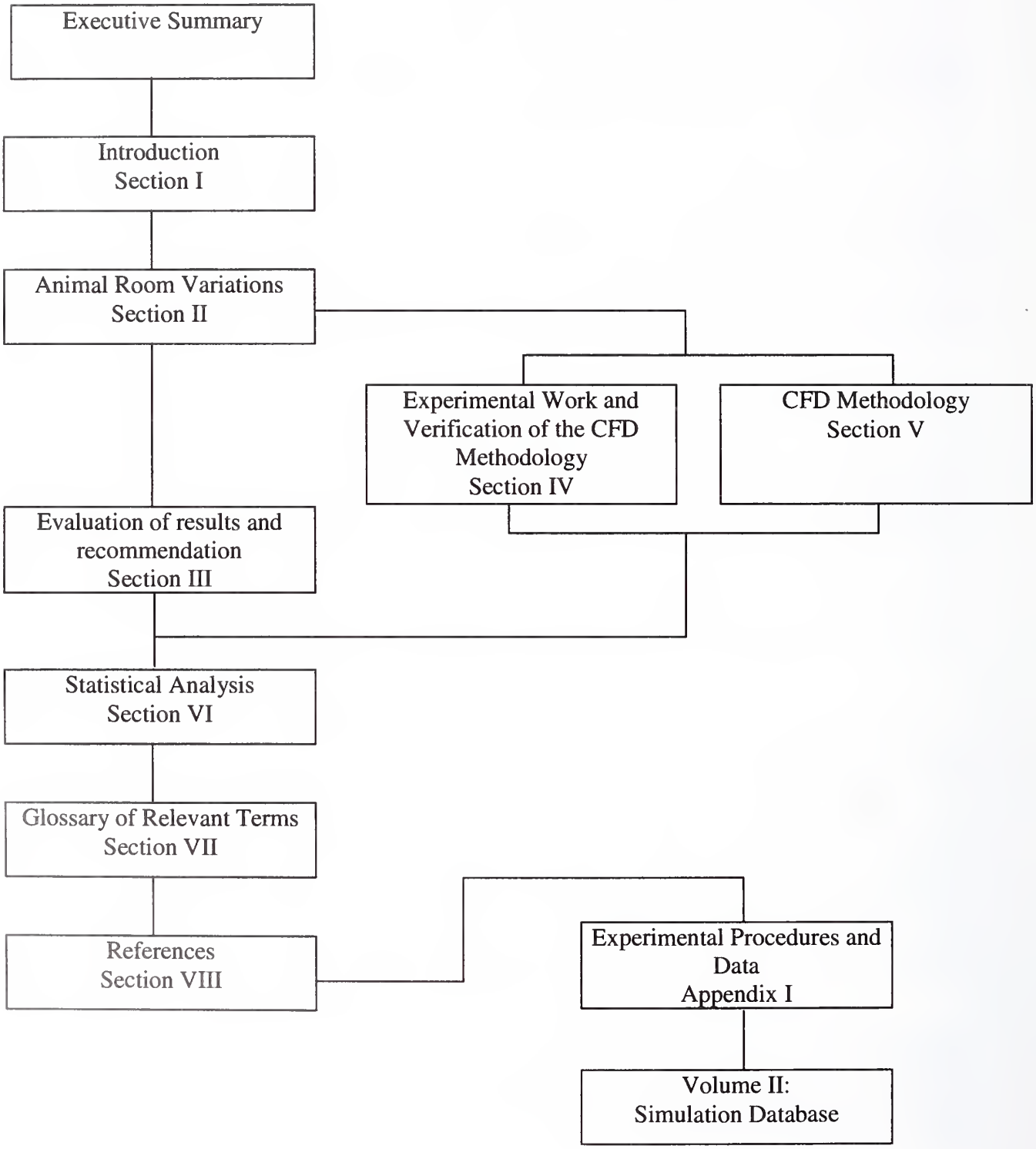
Section VII: Provides glossary of relevant CFD and experimental terms used in this project.

Section VIII: Complete listing of references.

Appendix I: Provides detailed information on the experimental procedures summarized in section 4 as well as full information on the raw data collected in these experiments.

Volume II presents two-page summary data for all 100 animal room simulations in the form of a picture of the case, a description, tabulated data, and histograms. Also included are a reprise of the description of the basecase room and the variations considered. Tables ranking the cases in ascending order on room and cage values of temperature, relative humidity, CO_2, and NH_3 concentration are also provided.

Road Map for Book



SECTION I

INTRODUCTION

SECTION I: TABLE OF CONTENTS

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1.0 INTRODUCTION

1.1 Objectives

This document describes a research program undertaken by the National Institutes of Health, Office of Research Services, Division of Engineering Services. The work was carried out in collaboration with the University of Illinois Bioenvironmental Engineering Research Laboratory (BERL) and Flomerics Inc.

The hypothesis of this research was that the room ventilation parameters, which include room ventilation rate, diffuser type, diffuser location, number of exhausts, exhausts location, cage density, changing station location, changing station status (on/off), room size, cage rack arrangement, and room pressurization, affect both room (macro) and cage (micro) environment for laboratory animal research facilities.

In order to develop relationships between micro- and macroenvironmental conditions and to better determine ventilation system designs that provide appropriate micro- and macroenvironments, the following objectives were set:

1. Conduct a study to determine typical mass generation rates of CO_2, H_2O, and NH_3, and consumption of O_2, with groups of mice in shoebox cages with bedding at different room air relative humidities using open-system calorimeters with precisely controlled fresh air exchange rates.

2. Create and measure various airflows within a known mouse cage in such a manner as to lay the groundwork for determining the boundary conditions for the computational fluid dynamics (CFD) analysis of the cage. Cage boundary conditions include resistance and coefficient of loss created by both the cage top and the surrounding edge on which the cage top sits. The tracer gas method using 1 L/min, and 100 mL/min injection rate for measuring the airflows within the cage was used. Comparison were conducted between tracer gas types CO_2 vs. SF_6, as well as changing airflow measurement techniques using a constant injection rate and decay methods.

3. Obtain data in an empty room as well as a room with racks, cages, and simulated animals to verify the accuracy of CFD. Room air velocity, temperature, and CO_2 concentration patterns were used throughout the room for verification of CFD model predictions.

4. Utilize over 500 CFD simulations to establish a relationship between micro- and macroenvironments by changing room ventilation rate, diffuser type, diffuser location, number of exhausts, exhausts location, cage density, changing station location, changing

station status (on/off), room size, cage rack arrangement, and room pressurization. The simulations' variations would determine the affect on both room (macro) and cage (micro) environments for laboratory animal research facilities.

1.2 Background to Project

Air quality within macro (room) and micro (cage) environments of laboratory animal facilities is essential for the health and welfare of humans and animals, and the integrity of the studies being conducted. It is well-known that biological responses are influenced by both genetic heritage and the environment. Information on the influence of the physical environment on the animals' biological responses is needed to improve laboratory animal facility design and management. At the optimum environmental condition, not only does the laboratory animal experience a state of well-being, the researcher obtains reliable and repeatable experimental results from the animal.

While many thousands of square feet of animal research facilities are designed and constructed each year, inadequate information is available regarding ventilation rates and patterns required to maintain acceptable micro- and macroenvironments. A scientific basis is needed for selecting the ventilation rates of the macroenvironment and microenvironment and for designing effective ventilation systems for laboratory animal facilities. Design information is also needed for engineers to improve design, ensure air quality, and minimize energy cost.

Current ventilation guidelines are based largely on anthropomorphic views as opposed to scientifically defined animal needs. Limited research has been conducted to determine macro- and microenvironment relationships in animal research facilities in regard to ventilation rates, room air distribution, supply relative humidity and temperature, and other factors required to maintain acceptable and uniform cage environments. Most research has focused only on room conditions.

Laboratory animal ventilation should balance air quality, animal comfort, and energy efficiency to provide cage environments that optimize animal welfare and research efficiency. Conditions that optimize animal welfare automatically tend to improve research efficiency because good conditions minimize unintended stress factors on the animals. Additionally, the laboratory animal ventilation system should provide a healthy and pleasant environment for researchers and animal caretakers.

On the subject of ventilation, the most commonly accepted sources of performance criteria for research animal facility ventilation systems are the *Guide for the Care and Use of Laboratory Animals*, Institute of Laboratory Animal Resources (1996) and the *American Society of Heating Refrigerating and Air Conditioning HVAC Systems and Application Handbook.*

Ventilation recommendations are based on room air exchanges, but cage ventilation rates may be inadequate in some cages and excessive in other cages depending on cage and facility design.

Recommendations for room ventilation rates of 10 to15 air changes per hour (ILAR, 1996) are an attempt to provide adequate ventilation for the room and the cages. This recommendation is based on the assumption that adequate ventilation in the macroenvironment provided sufficient ventilation to the microenvironment. This may be a reasonable assumption when cages have a top of wire rods or mesh. However, several studies have shown that covering cages with filter tops provide a protective barrier for rodents and reduced airborne infections/diseases, especially neonatal diarrhea, but can result in a significant differences in microenvironmental conditions due to changes in air movement caused by the cover.

1.3 Literature Review

The following is the conclusion of pertinent research studies and publications on room air distribution and the relationship between macro- and microenvironments, ambient temperature on growth, behavioral thermoregulatory responses in rats, and moisture production of rats and mice.

This section also includes a review of ammonia and carbon dioxide physiochemical properties and their relevance to the current study.

1.3.1 Literature Search on Macro and Micro Environmental Relationships

Carolyn K. Reeb, Robert B. Jones, David W. Bearg, Hendrick Bedigian, and Beverly Paigen: *Impact Of Room Ventilation Rates On Mouse Cage Ventilation And Microenvironment*, 1997, Contemp. Topics Lab. Anim. Sci., 36:74-79.

> To assess the impact of room ventilation on animal cage microenvironments, intracage ventilation rates, temperature, humidity, and concentrations of carbon dioxide and ammonia were monitored in non-pressurized, bonnet-topped mouse cages housing four C57BL/6J male mice that weighed 26.5 ± 0.4 g. with autoclaved pine shavings as bedding. The top, middle, and bottom rows of a mouse rack were monitored at room ventilation rates of 0, 5, 10, and 20 air changes per hour (ACH).
>
> - Ventilation inside the animal cage increased somewhat from 12.8 to 18.9 ACH as the room ventilation rate increased from 0 to 20 ACH, but the differences were not statistically significant. Most of the increases occurred in cages in the top row nearest to the fresh air supply. Cages containing mice had ventilation rates between 10 and 15 ACH even when room ventilation was reduced to 0 ACH. This ventilation is a result of the thermal heat load of the mice.
>
> - After six days of soiled bedding, intracage ammonia concentration was < 3 ppm at all room ventilation rates and was not affected by increasing room ventilation. Although

earlier reports, such as M.R. Gamble and G. Clough (1976), indicated ammonia values > 200 ppm, recent studies testing cage densities of four mice/microisolator cage, such as G.C. Choi, J.S. McQuinn, B.L. Jennings (1994), and J.J. Hasenau, R.B. Baggs, and A.L. Kraus (1993), are consistent with the observed data that ammonia concentration can be low. Two possibilities may explain why the ammonia concentrations were low. The first is that improved cage washing procedures and animal room cleanliness may reduce concentrations of ammonia-producing bacteria, resulting in lower ammonia concentration. In this facility, the cages are washed with water at 82 ±6 °C followed by a dry heat cycle at 118 °C. The second possibility is that formation of ammonia may be dependent on the strain of mice.

- Temperature inside the cages did not change with increasing ventilation. The temperature inside the cages was 1 to 3 °C higher than the room temperature, an observation consistent with an earlier study that proved the use of a filter top results in a temperature increase of about 2 °C in the cage.

- Humidity inside cages significantly decreased with increasing ventilation, from 55 percent relative humidity at 5 ACH to 36 percent relative humidity at 20 ACH. Humidity inside the cage increased compared with humidity in the room, and the average difference between room and cage RH was about 10 percent, similar to the increased cage humidity previously observed by M.L. Simmons, D.M. Robie, J.B. Jones, and L.J. Serrano (1968).

- Carbon dioxide concentration decreased from 2,500 ppm to 1,900 ppm when ventilation rate increased from 5 ACH to 10 ACH, but no further significant decrease was observed at 20 ACH. In conclusion, increasing the room ventilation rate higher than 5 ACH did not result in significant improvements in the cage microenvironment.

Guide For The Care And Use Of Laboratory Animals, Institute of Laboratory Animal Resources, 1996, National Research Council, National Academy Press, 23-55.

Microenvironment and macroenvironment: The microenvironment of an animal is the physical environment immediately surrounding it, the primary enclosure with its own temperature, humidity, and gaseous and particulate air composition. The physical environment of the secondary enclosure, such as a room, a barn, or an outdoor habitat constitutes the macroenvironment. Although the microenvironment and the macroenvironment are linked by ventilation between the primary and secondary enclosures, the environment in the primary enclosure can be quite different from the environment in the secondary enclosure. It is affected by the design of both enclosures. Measurement of the characteristics of the microenvironment can be difficult in small primary enclosures. Available data indicate that temperature, humidity, and concentrations of gases and particulate matter are often higher in an animal's

microenvironment than in the macroenvironment (Besch 1980; Gamble and Clough 1976; Murakami 1971; Serrano 1971; Flynn 1959). Microenvironmental conditions can induce changes in metabolic and physiologic processes and/or alterations in disease susceptibility (Schoeb and others 1982; Broderson and others 1976; Vesell and others 1976).

Temperature and Humidity: Regulation of body temperature within normal variation is necessary for the well-being of homeotherms. Generally, exposure of unadapted animals to temperatures above 85 °F (29.4 °C) or below 40 °F (4.4 °C) without access to shelter or other protective mechanisms might produce clinical effects (Gordon 1990) that could be life-threatening. Animals can adapt to extremes by behavioral, physiologic, and morphologic mechanisms, but such adaptation takes time and might alter protocol outcomes or otherwise affect performance (Gordon 1993; Garrard and others 1974; Pennycuik 1967). Environmental temperature and relative humidity can depend on husbandry and housing design and can differ considerably between primary and secondary enclosures. Factors that contribute to variation in temperature and humidity include housing material and construction, use of filter tops, number of animals per cage, forced ventilation of the enclosures, frequency of bedding changes, and bedding type.

Recommended dry-bulb temperatures for mice, rats, hamsters, gerbils, and guinea pigs are 18 to 26 °C (64 to 79 °F). However, some conditions might require increased environmental temperatures. These conditions include postoperative recovery, maintenance of chicks for the first few days after hatching, housing of some hairless rodents, and housing of neonates that have been separated from their mothers.

Ventilation: The purposes of ventilation are to supply adequate oxygen; remove thermal loads from animals, lights, and equipment; dilute gaseous and particulate contaminants; adjust the moisture content of room air; and, where appropriate, create static-pressure differentials between adjoining spaces. Establishing a room ventilation rate, however, does not ensure the adequacy of the ventilation of an animal's primary enclosure and hence does not guarantee the quality of the microenvironment. The degree to which air movement (drafts) causes discomfort or biologic consequences has not been established for most species. The volume and physical characteristics of the air supplied to a room and its diffusion pattern influence the ventilation of an animal's primary enclosure and so are important determinants of its microenvironment. The relationship of the type and location of supply air diffusers and exhaust vents to the number, arrangement, location, and type of primary enclosures in a room or other secondary enclosure affects how well the primary enclosures are ventilated and should therefore be considered. The use of computer modeling for assessing those factors in relation to heat loading and air diffusion patterns can be helpful in optimizing ventilation of primary and secondary enclosures. The guideline of 10 to 15 fresh-air changes per hour has been used for secondary enclosures for many years and is considered an acceptable general standard. Although it is effective in many animal housing settings, the guideline does not take into account the range of possible heat loads; the species, size, and number of animals involved; the type

of bedding or frequency of cage changing; the room dimensions; or the efficiency of air distribution from the secondary to the primary enclosure. In some situations, the use of such a broad guideline might pose a problem. A secondary enclosure that contains few animals could be over-ventilated and would waste energy. Under-ventilating a secondary enclosure that contains many animals would allowing heat and odor accumulation. To determine more accurately the ventilation required, the minimal ventilation rate (commonly in cubic feet per minute) required to accommodate heat loads generated by animals can be calculated with the assistance of engineers. The heat generated by animals can be calculated with the average-total-heat-gain formula as published by the American Society of Heating, Refrigeration, and Air-Conditioning Engineers ASHRAE (1997). The formula is species-independent, so it is applicable to any heat-generating animal. Minimal required ventilation is determined by calculating the amount of cooling required (total cooling load) to control the heat load expected to be generated by the largest number of animals to be housed in the enclosure, any heat expected to be produced by non-animal sources, and heat transfer through room surfaces. The total-cooling-load calculation method can also be used for an animal space that has a fixed ventilation rate to determine the maximal number of animals, based on total animal mass, that can be housed in the space. Even though that calculation can be used to determine the minimal ventilation needed to prevent heat buildup, other factors, such as odor control, allergen control, particle generation, and control of metabolically generated gases, might necessitate ventilation beyond the calculated minimum. When the calculated minimal required ventilation is substantially less than 10 air changes per hour, lower ventilation rates might be appropriate in the secondary enclosure, provided that they do not result in harmful or unacceptable concentrations of toxic gases, odors, or particles in the primary enclosure. Similarly, when the calculated minimal required ventilation exceeds 15 air changes per hour, provisions should be made for additional ventilation to address the other factors. In some cases, fixed ventilation in the secondary enclosure might necessitate adjustment of sanitation schedules or a limit on animal mass to maintain appropriate environmental conditions.

G.L. Riskowski, R.G. Maghirang, and W. Wang: *Development Of Ventilation Rates And Design Information For Laboratory Animals Facilities*, Part 2-Laboratory Tests, 1996, ASHRAE Transactions, V.102, Pt. 2, RP-730.

Eight ventilation parameters for laboratory animal facilities were studied in a full-scale room ventilation simulator. They were room air exchange rate, diffuser neck diameter, diffuser type, number of returns, return location, cage type, room size and cage rack arrangement. Air exchange rates, velocities, and temperatures within the room and the cages were studied as well. Room airflow pattern and cage airflow patterns were determined using smoke tests. Cage conditions varied widely among cages within the same room. Cage type was the most important factor influencing cage conditions. Room air exchange rate, air velocity approaching the cage, number of returns, return location, and diffuser type did not significantly influence cage conditions in the ranges studied.

Room air velocities approaching the cage were not high enough to have a major influence on shoebox cage ventilation rates. Air diffusion performance index (ADPI) did not show a difference between the diffuser type, the number of returns, or return location, but ADPI did show a difference with the room ventilation rate and diffuser neck size.

The air velocity, air temperature, and ventilation rate were measured in the room and within cages at selected locations in the room. The following conclusions were drawn:

- Cage conditions varied widely with cage location in a room.

- Cage type was the most important factor that influenced cage conditions. Wire cages had ventilation rates three times higher than shoebox cages even though the sensible heat production in the wire cage was only one-fourth that of the shoebox cage.

- In general, room air exchange rates, velocity approaching the cage, number of returns, location of return, and diffuser type did not significantly influence cage conditions for a range of factors studied in this project. Room air velocities approaching the cage were not high enough to have a major influence on shoebox cage ventilation rate.

- The thermal comfort conditions in the human-occupied region of laboratory animal rooms were affected by room ventilation rate. In general, ADPI had lower values at lower ACH.

- ADPI did not show a difference between the diffuser types, the number of returns, or the return location, however, the diffuser neck size (neck velocity) did affect the ADPI values.

For the range of conditions tested in this study, the number of air returns and the location of air returns did not have a measurable effect on cage or room conditions. The perforated ceiling and laminar flow diffuser performed equally well, but the neck size needs to be carefully matched to the overall design. Room ACH values from 5 to 15 had the same effect on cage conditions, so the higher room air exchange rates did not provide better conditions for the animals.

This study did not address the concern of odors and contaminants in the room or the cages. This needs further study. However, higher ventilation rates in the cages were found to reduce contaminant levels in the cages. Another area that needs more study is cross-contamination between cages due to air movement from cage to cage. More study is needed to explain the wide variation of cage conditions at different locations in the same room. The magnitude of air velocity approaching the cage did not have a large effect on cage ventilation rate at the low room velocities encountered in this study. However, the direction of airflow approaching the cage could have a major effect and could explain some of the differences. More precise measurements are needed on effects of air direction and magnitude on cage ventilation rates.

Scott Perkins and Neil S. Lipman: *Characterization And Quantification Of Microenvironmental Contaminants In Isolator Cages With A Variety Of Contact Beddings*, 1995, Contemp. Topics Lab. Anim. Sci., 173:96-113.

Microenvironmental contaminants were measured within isolator-type cages housing DBA/1J mice on eight contact beddings. Each cage contained 850 cm^3 of bedding and five mice randomized by body weight. Seven cages with and two to four cages without mice were evaluated per bedding. Macroenvironmental conditions were defined and controlled. Macro- and microenvironmental temperatures, relative humidity, and carbon dioxide and ammonia concentrations were determined daily during each of three 7-day test periods. An air sampling pump and detector tubes were used to measure hydrogen gas,
2-butanol, acetone, ethanol, carbon monoxide, acetic acid, hydrogen sulfide, sulfur dioxide, and formaldehyde on the final day of each test period. In addition, gas chromatographic analysis was used on the seventh day to detect additional volatile alcohols and ketones. Ammonia concentrations ranged from 0 to 410 ppm, depending on the bedding type and day of measurement. On the basis of the mean microenvironmental ammonia concentration in the cages with mice, the beddings were ranked from highest to lowest in ammonia generated, as follows: aspen shavings, pine shavings, reclaimed wood pulp bedding, virgin pulp loose bedding, hardwood chip bedding, recycled paper bedding, virgin cellulose pelleted bedding, and corn cob bedding. The temperature, relative humidity, and carbon dioxide concentration were similar among beddings. No other contaminants were detected except acetic acid (mean = 0.86 ppm) in the cages with and without mice containing corncob bedding. Sulfur dioxide (mean = 0.42 ppm) was only detected in cages with mice and corncob bedding. In summary, the concentration of ammonia generated varied significantly in cages containing mice and different contact bedding.

- Temperature: There were no significant differences in temperature detected among cages with mice and various bedding throughout the 7-day observation periods. Temperature rise in the cages with hardwood chip bedding was approximately 4 °F.

- Relative humidity: Intracage relative humidities were not significantly different among cages with different bedding through the 7-day observation periods. Relative humidity rise in the cages with hardwood chip bedding was approximately 25 percent.

- Carbon dioxide: There were no significant variations detected in carbon dioxide concentration among cages with various bedding throughout the 7-day observation periods. Carbon dioxide concentration in the cages with hardwood chip bedding was approximately 4,500 ppm with background concentration of 370 ppm.

- Ammonia: Microenvironmental ammonia concentration ranged from 0 to 410 ppm, depending on the bedding type and day of measurement. The cages containing aspen shavings had a significantly higher 7-day mean ammonia concentration compared with other beddings. Additionally, the cages containing reclaimed wood pulp and pine shavings had a significantly higher 7-day mean ammonia concentration compared with other beddings, with the exception of aspen shavings. Cages containing virgin pulp loose bedding had a significantly higher 7-day mean ammonia concentration compared with the cages that had virgin cellulose and corncob bedding. Ammonia was first detected in cages containing aspen and pine shavings on day 2. On day 3, ammonia was first detected in cages containing reclaimed wood pulp. Cages with virgin loose pulp and hardwood chip bedding had detectable ammonia beginning on day 4, followed by the cages with recycled paper bedding on day 6. The cages containing virgin cellulose bedding had no detectable ammonia production until day 7, whereas the cages with corncob bedding never had detectable ammonia concentration. There was a significant difference in ammonia concentration in cages with different bedding and the day of evaluation, indicating that ammonia production differed among the beddings over time.

R.G. Maghirang, G.L. Riskowski, L.L. Christianson, and Paul C. Harrison: *Development Of Ventilation Rates and Design Information for Laboratory Animal Facilities*, Part 1-Field Study, 1995, ASHRAE Transactions, V. 101, Pt. 2, RP-730.

A survey was conducted of 46 laboratory animal rooms (33 rat rooms, 8 mouse rooms, 2 rabbit rooms, 2 primate rooms, and 1 dog room) at three commercial use sites, five universities, and a research organization. Air exchange rates, air velocities, temperature, humidity, ammonia concentrations, noise levels, and light levels were measured throughout the room and within selected cages in the room. Cage conditions varied widely among cages within the same room and among similar cages in different rooms. Cage type was the most important factor that influenced cage conditions and uniformity in cage conditions. Room air exchange rate had little influence on cage conditions. Velocity approaching the cage, number of returns and diffusers, and diffuser type did not significantly influence cage conditions and uniformity in cage conditions.

The following conclusions were drawn:

- Cage conditions varied widely among cages within the same room and among similar cages in different rooms.

- Cage type was the most important factor that influenced cage conditions and uniformity in cage conditions.

- Room air exchange rate, air velocity approaching the cage, number of returns and diffusers, and diffuser type did not significantly influence cage conditions and uniformity in cage conditions.

Gwen C. Choi, Jennifer S. McQuinn, Brenda L. Jennings, Daniel J. Hassett, and Scott E. Michaels: *Effect of Population Size on Humidity and Ammonia Levels in Individually Ventilated Microisolation Rodent Caging*, 1994, Contemp. Topics Lab. Anim. Sci., 33:77-81.

A study was undertaken to determine the effect of population size on the buildup of ammonia and humidity in individually ventilated microisolation cages over time as compared with static microisolation cages. Ammonia and relative humidity measurements were taken daily from sterilized, pressurized, individually ventilated microisolation cages and sterilized, static microisolation cages containing one to four, 24 to 26 gram female Crl: CF-1 BR mice per cage. The effect of population size was evaluated over a 32-day period in the ventilated cages and over a 10-day period in the static cages. The bedding in each cage was 140 grams (360 cm^3) of combination 1/4-in and 1/8-in. No detectable levels of ammonia were present in any of the ventilated cages throughout the duration of the study. Ammonia was detected after eight days in the static microisolation cages containing three or four mice. Relative humidity levels in ventilated cages were not significantly different than room relative humidity levels indicating that the ventilation provided to the microisolation cages was effective in controlling intracage humidity. Relative humidity levels in static microisolation cages were significantly higher than room humidity levels, and a significant increase in relative humidity with increasing population density was observed. The complete lack of detectable ammonia levels in the ventilated cages and the low levels of ammonia detected in the static cages may have been influenced by the stock of animal studied, the autoclaving of the bedding, and the differences in ventilation rates of the two caging types.

- The intracage relative humidity was approximately 23 percent to 36 percent higher than the room relative humidity depending on cage population density.

- No ammonia was detected during the study period in cages containing one or two mice. Ammonia was detected after eight days in cages containing three or four mice. On days 9 and 10, the contrast of ammonia production between low population density (one or two mice/cage) and high population density (three or four mice per cage) was statistically significant.

M.J. Huerkamp and N.D.M. Lehner: *Comparative Effects of Forced-Air, Individual Cage Ventilation on an Absorbent Bedding Additive in Mouse Isolator Cage Microenvironment*, 1994, Contemp. Topics Lab. Anim. Sci., 33(2)58-61; J.J. Hasenau, R.B. Baggs, and A.L. Kraus: *Microenvironments in Microisolation Cages Using BALB/C and CD-1 Mice*, 1993, Contemp. Topics Lab. Anim. Sci.,32(1)11-16, 32(2)58-61; G.R. Gale and A.B. Smith: *Ureolytic and*

Urease-Activating Properties of Commercial Laboratory Animal Bedding, 1981, Lab. Anim. Sci. 31:56-59; H. Murakami: *Differences Between Internal and External Environments of the Mouse Cage*, 1971, Lab. Anim. Sci. 21:680-684.

Ammonia production by bacteria can be influenced by the strain or stock of animal as well as by population density, relative humidity, temperature, and type of cage bedding. Strain, stock and sex differences in ammonia production have been shown with BALB/c mice producing less ammonia than CDl mice. For mice housed in microisolator cages, ammonia concentrations were > 100 ppm for strains DBA and CD-1 and approximately 21 ppm for strain BALB/c on the 7th day of soiled bedding.

R.G. Maghirang, G. L. Riskowski, L. L. Christianson, and P. C. Harrison: *Environmental Management of Laboratory Animals*, Research Needs, 1994, ASHRAE Transactions, V.100, Pt. 2, OR-94-16-1.

Recognizing the research needs for laboratory animal facility design and management is important for both cost-effective design of laboratory research animal facilities and the reliability of laboratory animal experiments. The Laboratory Animal Consortium (LAC), which consists of representatives from various industries and organizations involved with laboratory animals, has identified the following five major research priorities: the effects of microenvironmental conditions on the response of laboratory rats, the means for achieving appropriate ranges of environmental conditions, the environmental preferences of rats, the relationships between cage and room environmental conditions in typical laboratory animal facilities and caging systems, and the practical methods for measuring cage environmental conditions.

Recognizing the research needs for laboratory animal facility design and management is important for both cost-effective design of animal facilities and reliability of experimental procedures. The LAC, consisting of representatives from various organizations involved with laboratory animals, has identified five major research priorities:

- Effects of micro environmental conditions on the heat, moisture, gas, and particulate production rates of rats;
- Practical means for achieving appropriate ranges of environmental conditions;
- Environmental preferences of rats;
- Relationship between cage and room environmental conditions in typical laboratory animal facilities and caging systems; and
- Practical methods for measuring cage environmental conditions.

This research agenda will ultimately provide scientifically based criteria for laboratory animal facility design and management, improve the scientific validity of research using laboratory animals, enable managers to adjust the animal facility systems and practices to conform to animal welfare guidelines, and develop a basis for reducing animal facility design and operational costs. It should be noted that meeting this challenge requires the following three other activities:

- Adequate funding and support from both public and private organizations,
- Conduct of research by multidisciplinary teams, and
- Evaluation and utilization of research results.

S. Frei: *Facilities Approaches To Reducing Operating Costs*, 1993, Affiliated Engineers, Inc.

Frei noted that scientific justification for recommended ventilation rates is rather weak. The 1985 ILAR (Institute of Laboratory Animal Resources) Committee on Care and Use of Laboratory Animals recommendations can be traced back to Munkelt's (1938) work, in which he proposed a ventilation rate of 1.5 cfm/lb for rats or guinea pigs. A historical summary of the development of ventilation rates follows:

- Munkelt (1938) developed a standard of 1.5 cfm/lb of animal or 11 air changes per hour while working with rats and guinea pigs.
- Runkle (1964) extrapolated Munkelt's (1938) rates for mice through dogs.
- In 1964, a laboratory extrapolated Runkle's (1964) work to imply 10 to 20 air changes per hour (Frei 1993).
- ILAR (1978) set the first standards at 10 to 15 air changes per hour.

John J. Hasenau, Raymond B. Baggs, and Alan L. Kraus*: Microenvironments In Microisolation Cages Using BALB/C And CD-1 Mice*, 1993, Contemp. Topics Lab. Anim. Sci.,32(1)11-16, 32(2)58-61.

Four different mouse caging systems were evaluated for microenvironmental temperature, humidity, and ammonia levels. All had polycarbonate bases and lids holding Reemay 2024 filter material in three different designs or a control without filter. Comparisons were made of BALB/c and CRL: CD-1 (ICR) BRV mice at four and two per cage under different macroenvironmental (room) conditions. All studies were conducted in an animal room measuring 11 ft. x 8.58 ft. x 8.0 ft. in an AAALAC accredited animal facility.

Ventilation of 20 air changes per hour was balanced so that pressure differences allowed air to flow from the corridor and ceiling supply vent (130 CFM) over the entry door through the room into the far wall exhaust ceiling vent (270 CFM). A 12/12-hour light/dark cycle with no twilight was used. Room temperatures averaged 22.8 ± 1.7 °C (range 18.4 to 26.9 °C) in the trials where nationally accepted standard macro environment RHs were used and averaged 24.1 ± 0.7 °C (range 22.2 to 25.2 °C) during below normal macroenvironmental RH trials. The average range in room temperature per trial was ± 1.35 °C. Room humidity in the standard RH group was 51.5 ± 8.2 percent (range 38.5 to 66.5 percent RH). Room humidity in the below normal RH group was 22.7 ± 7.7 percent (range 11.4 to 35.1 percent RH). The range in room humidity per trial averaged 11.7 percent RH. At macroenvironmental room humidities of 40 to 70 percent, the relative humidity (RH) levels in the microisolation cages with four animals per cage averaged 27.1 percent RH above room RH levels. With two animals per cage, the RH levels in the microisolation cages averaged 16.1 percent RH above the room RH levels. At macroenvironmental room humidities of <40 percent, the RH levels in microisolation cages with four animals averaged 35.4 percent RH above the room RH levels. At two animals per cage the RH levels in the microisolation cages averaged 22.6 percent above room levels.

- Study I (BALB/c mice): Population density of four animals per cage (Trials 1 and 2):

  Temperature: There was no significant temperature variation between microisolator caging systems.

  Relative humidity: Microenvironmental RH in the type microisolator cages averaged 28 percent higher than the room RH levels.

  Ammonia: All cages accumulated less than 5 ppm ammonia at day 9.
- Study I (BALB/c mice): Population density of two animals per cage (Trials 3 and 4):

  Relative humidity: Micro environmental RH in microisolator cages averaged 9 percent higher than the room RH levels.

  Ammonia: All cages contained less than 3 ppm ammonia at day 9.

- Study II (CD-1 mice): Population density of four animals per cage (Trials 1 and 2):

  Relative humidity: Micro environmental RH in microisolator cages averaged 36 percent higher than the room RH levels.

  Ammonia: In trial 1, 8-day trial averages were, 50.6 ppm, in microisolator cages. In trial 2, 8-day trial averages were 8.7 ppm, in microisolator.

- Study II (CD-1 mice): Population density of two animals per cage (Trials 3 and 4):

  Relative humidity: Micro environmental RH in microisolator cages averaged 13 percent higher than the room RH levels.

  Ammonia: All cages accumulated less than 5 ppm at day 8. There were no significant sex differences or significant differences in cages with replaced damaged filters in any of the parameters measured in either of the two studies. Air velocity across each cage and shelf of the rack was 0 to 0.65 m/second. The outermost cages were subject to the highest air velocity.

- Study 3 (Strain/stock comparison):

  Temperature: The CD-1 cages, DBA cages, and BALB/c cages measured 23.5 to 23.6 °C, which were not significantly different.

  Relative humidity: With average humidities measured at CD- 1 cage (82.9 percent), DBA cage (86.3 percent), and BALB/c cage (79.0 percent), only the BALB/c cages had significantly lower humidities than the DBA cages. For four mice housed in microisolator cages Ammonia time period averages (day 7) were CD-1 = 149.5 ppm, DBA = 214.2 ppm, and BALB/c = 21.1 ppm.

J.J. Hasenau, R.B. Baggs, and A.L. Kraus: *Microenvironments in Microisolation Cages Using BALB/C And CD-1 Mice*, 1993, Contemp. Topics Lab. Anim. Sci., 32(1)11-16, 32(2)58-61; B.F. Corning, and N.S. Lipman: *A Comparison of Rodent Caging Systems Based on Microenvironmental Parameters*, 1991, Lab. Anim. Sci., 40:498-508; N.L. Sato, And M. Fukui: *Dehumidification of Ventilation Air in a Barrier Maintenance System for Laboratory Animals*, 1989, Lab. Anim. Sci., 39:448-450; D. Wu, G.N. Joiner, and A.R. McFarland: *A Forced-Air Ventilation System for Rodent Cages*, 1985, Lab. Anim. Sci., 35:499-504; Gamble, M. R., and G. Clough: *Ammonia Build-Up in Animal Boxes and its Effect on Rat Tracheal Epithelium*, 1976, Lab. Anim. Sci. (London), 10:93-104.

It was shown that ammonia is produced in greater amounts under conditions of high humidity. Desiccation was shown to be helpful in the prevention of ammonia and humidity accumulation as urease-producing bacteria grow less efficiently in the presence of reduced humidity. Lowering the macroenvironmental relative humidity levels and providing dehumidified air have been suggested as methods for preventing the elevation of humidity observed in barrier caging systems.

C.M. Collins and S.E.F. D'Orazio: Bacterial Ureases-Structure, *Regulation Of Expression and Role in Pathogenesis*, 1993, Mol. Microbiol, 9:907-913; M. Dixon: D-Aspartate Oxidase, 1970,

Academic Press, Inc., 713-718.

Ammonia is produced by enteric bacteria through two possible mechanisms of enzymatic activity. Bacterial ureases can catalyze the hydrolysis of urea to ammonia and carbamate. A second series of enzymes, D-and L-amino acid oxidases can deaminate amino acids to their corresponding keto acid and ammonia.

Y. Zhang, L.L. Christianson, G.L. Riskowski, B. Zhang, G. Taylor, H.W. Gonyou, and P.C. Harrison: *A Survey of Laboratory Rat Environments*, 1992, ASHRAE Transactions: Symposia, 98(2)247-253.

A survey of laboratory animal environmental conditions in seven laboratory rat rooms was conducted. These rooms were designed and operated according to the ILAR (1985) guidelines, which recommended at least 10 ACH. Room air changes varied from 11 to 24 ACH, room air ammonia levels were under 0.5 ppm, and macroenvironmental conditions were considered satisfactory. However, cage air quality conditions and ventilation rates in typical rat cages may be "inadequate, which" or "inadequate and could" compromise the rat's respiratory systems. For those same rooms, ammonia levels ranged from negligible to 60 ppm in the cages. The authors noted that designs based only on room air changes may not be adequate to achieve desired conditions in the animal cages.

Brian F. Corning and Neil S. Lipman*: A Comparison of Rodent Caging Systems Based on Microenvironmental Parameters*, 1991, Lab. Anim. Sci., 40:498-508.

Four different mouse caging systems were evaluated for micro environmental temperature, carbon dioxide, relative humidity (RH) and ammonia levels during a 7-day testing period. All caging systems evaluated had polycarbonate bases and consisted of either a molded polyester (MP) filter lid, one of two different polycarbonate filter lids, or no filter lid which served as a control. At 50 percent macro environmental RH (study I), all systems maintained an intracage temperature of 75.5 °F ± 0.5 °F. Both polycarbonate systems averaged > 2,200 ppm of carbon dioxide, more than the MP system and the controls. When compared with RH in the control cages, RH levels averaged over 20 percent and five to eight percent RH greater in the polycarbonate filter lid systems and the MP system, respectively. There were no appreciable ammonia levels in either the MP or control systems. In the polycarbonate filter lid systems, ammonia levels were detectable on day 4 and were > 200 ppm by day 6. At 20 percent macro environmental RH (Study II), there was a proportional 15 to 30 percent RH decrease from study I levels. Ammonia levels were undetectable in any system until day 7 and averaged only 17 ppm in one of the polycarbonate systems. Minimal differences were observed in studies III, IV and V when pine shavings were used instead of hardwood chips, a CD-1 stock instead of a DBA/2J strain, and different grades of filter inserts in the polycarbonate systems, respectively.

- Study I:

  The temperature range for all caging systems was 75.5 °F ± 0.5 °F.

  Carbon dioxide: The Microisolator and Micro-Barrier systems averaged greater than 2,200 ppm more CO_2 than those in the molded polyester system which was 2,900 ppm greater than the control. The control cage CO_2 levels of 316 ppm approximated the 279 ppm in the macro environment.

  Relative humidity: Microenvironmental humidity levels in the Microisolator and Micro-Barrier systems averaged greater than 20 percent RH higher than in the control cages. RH in one cage reached over 85 percent.

  Ammonia: Weekly NH_3 levels in the control cages were 1.6 ppm and the molded polyester systems were 0.9 ppm. Weekly levels for the Microisolator and Micro-Barrier systems were 139.1 ppm and 162.8 ppm of NH_3 respectively. By day 4, one of the Micro-Barrier cages was already at 260 ppm NH_3, the maximum level attainable for the sampling tube. By day 6, seven of eight cages from the Microisolator and Micro-Barrier systems contained greater than 200 ppm of NH_3.

- Study II:

  There were no significant temperature variations among caging systems at 20 percent macro environmental humidity.

  Carbon dioxide: Similar trends, as in study I, were observed for CO_2 levels among caging systems at the lower room humidity. No significant differences were observed when compared to study I.

  Relative humidity: There was a proportional 15 to 30 percent RH decrease in microenvironmental RH levels in all caging systems when macroenvironmental humidity was lowered to 20 percent RH. Similar trends were observed among caging systems when compared with humidity levels in study I.

  Ammonia: Weekly intracage NH, levels, which averaged 139.1 and 162.8 ppm for the Microisolator and Micro-Barrier caging systems respectively, when macro environmental humidity was 50 percent RH, were reduced to four and 17 ppm of NH_3 for these systems when room humidity was reduced to 20 percent. Ammonia detection at the lower humidity was not evident until day 7. There were no detectable NH_3 levels in any of the molded polyester or control cages at 20 percent macroenvironmental humidity.

- Study III:

  Temperature: No significant temperature differences were observed when pine shavings were used instead of hardwood chips.

  Carbon dioxide: There were statistically significant ($P < 0.05$) elevations in CO_2 levels in all caging systems when pine shavings were used. The molded polyester system averaged 1,157.8 ppm versus 967.9 ppm with hardwood chips. The Microisolator and Micro-Barrier systems averaged 3,485.9 ppm and 3,651.6 ppm with pine shavings versus 3,187.5 ppm and 3,616.1 ppm with hardwood chips. Trends among caging systems were similar to those observed when hardwood chips were used.

  Relative humidity: There were similar trends to studies I and II in RH and no significant differences were observed when shavings were used.

  Ammonia: There were similar trends to studies I and II and no significant differences in NH_3 levels were observed when pine shavings were used.

- Study IV:

  Temperature: No significant differences in temperature were detected when the CD-1 stock was used instead of the DBA/2J strain.

  Carbon dioxide: There were statistically significant ($P < 0.05$) elevations in CO_2 levels when the CD-1 stock was used in the Microisolator and Micro-Barrier caging systems. The Microisolator system averaged 4351.8 ppm versus 3187.5 ppm with the DBA/2J strain. The Micro-Barrier system averaged 4376.8 ppm versus 3616.1 ppm with the DBA/2J strain. Trends among caging systems were similar to those noted when the DBA/2J strain was used.

  Relative humidity: There were significantly higher humidity levels ($P < 0.05$) within the Microisolator cage type with the CD-1 stock (79.5 percent RH vs. 69.7 percent RH). Trends among caging systems were similar to those noted when the DBA/2J strain was used.

  Ammonia: Trends in ammonia levels among caging systems were similar to those noted when the DBA/2J strain was used. No significant differences were observed.

- Study V:

  No significant differences were observed between polycarbonate systems having

either a Reemay filter insert or when the two different frames were compared for temperature, CO_2, relative humidity, or NH_3. Daily NH_3 levels detected in study V were as high as 450 ppm with humidities over 90 percent RH in individual cages from the Microisolator and Micro-Barrier systems. Detector tubes with the broader range of 50 to 900 ppm of NH_3 were used for this study.

Lynn S.F. Keller, William J. White, Michael T. Snider and C. Max Lang: *An Evaluation of Intra-Cage Ventilation in Three Animal Caging System*, 1989, Lab. Anim. Sci., 39:237-242.

Although temperature and relative humidity have been quantified and their effects on research data studied, few studies have measured the air turnover rates at cage level. We evaluated the air distribution and air turnover rates in unoccupied shoebox mouse cages, filter-top covered cages, and shoebox mouse cages housed in a flexible film isolator by using discontinuous gas chromatography/mass spectrometry and smoke. Results showed that air turnover was most rapid in the unoccupied shoebox mouse cage and slowest in the filter-top covered cage. Placing mice in the filter-top covered cage did not significantly improve the air turnover rate. Although filter-top covered cages reduce cage-to-cage transmission of disease, the poor airflow observed within these cages could lead to a buildup of gaseous pollutants that may adversely affect the animal's health.

T.J. Van Wrinkle, M.W. Balk: *Spontaneous Corneal Opacities in Laboratory*, 1986, Lab. Anim. Sci., 36:248-255; G.L Keller, S.F. Mattingly, F.B. Fnapke, Jr.: *A Forced Air Individually Ventilated Caging System for Rodents*, 1983, Lab. Anim. Sci., 33:580-581; G.R. Gale, A.B. Smith: *Ureolytic and Urease-Activating Properties of Commercial Laboratory Animal Bedding*, 1981, Lab. Anim. Sci., 31:56-59; J.R. Lindsey, M.W. Connor, H.J. Baker: *Physical, and Microbial Factors Affecting Biological Response in Animal Housing*, 1978, National Academy of Sciences, 31-43; M.R. Gamble, G. Clough *Ammonia Build-Up in Animal Boxes and its Effect on Rat Tracheal*, Lab. Anim. (London), 10:93-104,1976.

Carbon dioxide and ammonia are the major gaseous pollutants generated by animals and animal waste within the cage. Ammonia levels in an animal's environment are dependent on fecal bacteria flora, population density, frequency of bedding changes, type of bedding material, cage design, temperature, humidity, cage sanitation, ventilation, and the animal's level of activity.

Louis J. Serrano: *Carbon Dioxide and Ammonia in Mouse Cages: Effect of Cage Covers, Population, and Activity*, 1971, Lab. Anim. Sci., 21:75-85.

To determine the affect of rod, wire-mesh, and fibrous filter types of covers on diffusion or convection of gases produced in the cage, groups of 4, 8, or 16 mice were placed in cages. Samples of air from each cage were analyzed daily. Filter and mesh covers had a major influence on the composition of air in the cages. They allowed the accumulation of CO_2, NH_3, and probably other gases to rise to levels considerably higher than in cages with open covers. When the mice were active, or when the number of mice in the cage was doubled, the CO_2 level was increased 50 to 100 percent above the original level of each cage. NH_3 was not detected until the 3rd to 6th day (3rd day for 16 mice per cage and to 6th day for 4 mice per cage), depending on the number of mice per cage. By the 7th day air reached noxious levels under some covers. Limiting the number of mice per cage and frequently removing soiled bedding could prevent excessive levels of CO_2 and NH_3 from accumulating in protectively covered cages.

- Significance of ammonia levels: Ammonia was not detected until the 5th or 6th day in a protectively covered cages holding no more mice than the number recommended for its size.

- Carbon dioxide is a metabolic by product of respiration and its accumulation is influenced by activity level of the animals, population density, and airflow within the cage. CO_2 levels were significantly higher in all cages than in the room. The levels in protective cover cages were in the range of 1217 parts per million for 4 mice per cage to 3155 parts per million for 16 mice per cage.

T.R. Schoeb, M.K. Davidson, and J.R. Lindsey: *Intracage Ammonia Promotes Growth of Mycoplasma Pulmonis in the Respiratory Tract of Rats*, 1982; J.R Broderson, J.R. Lindsey, J.E. Crawford: *The Role of Environmental Ammonia in Respiratory Mycoplasmosis of Rats*, 1976, Am. J. Path., 85:115-130.

Ammonia concentrations >25 ppm promote the growth of infective agents in the respiratory tracts of rats.

M.L. Simmons, D.M. Robie, J.B. Jones, and L.J. Serrano: *Effect of a Filter Cover on Temperature and Humidity in a Mouse Cage*, 1968, Lab. Anim., 2:113-120.

To determine how a filter cap affects the heat and moisture buildup in a mouse cage and how that buildup is affected by ambient conditions of temperature and relative humidity, 50 adult female mice were housed 10 per cage in polycarbonate cages that were covered with a fibrous filter and sealed with a neoprene gasket and hold-down rod. The cages were placed in a chamber that controlled ambient temperature and humidity. Observations were made at 1 °F intervals of temperature 68 to 74 °F and at three different

relative humidities (40, 55, and 70 percent). Every 24 hours the chamber conditions were changed, and cage, bedding, water, filter caps, and food were replaced. Three sensors suspended just under the filter cover measured temperature and humidity and transmitted the data to a recorder. The first reading was taken after a 3-hour equilibration period, then every three hours until the next day's change. By measuring the average temperature and humidity, it was possible to study the differences between cage and ambient conditions. At 68 °F and 40 percent relative humidity, the mean conditions in the cage were 72 °F and 50 percent relative humidity; at the upper limit of 74 °F, and 70 percent relative humidity, the mean cage conditions were 78 °F and 75 percent relative humidity.

R.S. Runkle: *Laboratory Animal Housing*, 1964, Amer. Inst. Arch. J., 41:77-80; F.H. Munkelt: *Air Purification and Deodorization by Use of Activated Carbon*, 1948; F.H. Munkelt: *Odor Control in Animal Laboratories*, 1948, Refrig. Engr., 56:222-229.

Most of the current recommended guidelines for heating, ventilation, and air conditioning systems for the animal research facilities appear to be based on the ventilation criteria described by Runkle, which were in turn based on studies done by Munkelt.

1.3.2 Literature Search on Effects of Ambient Temperature on Growth and Behavioral Thermoregulatory Responses in Mice

Christopher J. Gordon, Peggy Becker, and Joseph S. Ali: *Behavioral Thermoregulatory Responses of Single- And Group-Housed Mice*, 1997, Neurotoxicology Division, National Health and Environmental Effects Research Laboratory, U.S. Environmental Protection Agency, Physiology and Behavior (accepted for publication).

The ambient temperature (T_a) to house and study laboratory mice is critical for nearly all biomedical studies. The ideal T_a for housing mice should be based on their thermoregulatory requirements. The T_a for housing mice should approximate their zone of thermoneutrality where neither autonomic nor behavioral thermoeffectors are activated. In other words, the T_a for housing should not stress the animal's thermoregulatory system. Although laboratory mice are usually housed in groups of five or more, most of the information on thermoregulation in mice has been collected in individual animals. Overall, individual mice have a thermoneutral zone of approximately 30 to 32 °C, which is considerably warmer than the standard housing T_a of 22 to 24 °C. Thus, it is expected that standard housing conditions impart varying amounts of cold stress on mice. However, because they frequently huddle and thereby reduce heat loss it can been assumed that a standard housing T_a of 22 to 24 °C is probably not thermally stressful for groups of mice. If huddling behavior alters the thermoneutral zone, then groups of mice should prefer markedly cooler T_as compared to individual mice. To address this issue, it is necessary to measure the thermoregulatory behavior of individual

and groups of mice. In one study, female CD-1 mice were housed in groups of five or individually in a temperature gradient while selected T_a and motor activity were monitored. Single- and group-housed mice displayed a circadian oscillation of selected T_a with relatively warm T_a of ~29 °C selected during the daytime and cooler T_a of ~ 25 °C during the night. Motor activity was low during the day and high at night. Selected T_a of aged (11 month old) mice was ~1.0 °C warmer for single mice as compared to groups. Thermal preference of younger mice (two months old) was similar for individual- and group-housed animals. In another study, autonomic thermoregulatory requirements were measured in groups of female CD-1 mice that were placed inside a direct calorimeter. Groups of five mice displayed a minimal metabolic rate at a T_a of 30 °C. As T_a decreased below 30 °C, metabolic rate increased in a near linear fashion. Thus, groups of five mice display a metabolic profile that is qualitatively similar to individual mice. Their zone of metabolic thermoneutrality is approximately 30 °C. Daytime metabolic rate has not been determined in groups of mice. The operative T_a of mice housed in standard facilities was estimated by measuring the cooling rate of "phantom" mice modeled from aluminum cylinders. The results show that the typical housing conditions for single- and group-housed mice are much cooler than their T_a for ideal thermal comfort. Wood shaving bedding material provides the best type of insulation that allows mice to maintain a relatively warm microenvironment. Wire-screen floors and wood chip bedding has minimal thermal insulative value.

- To summarize, groups of five mice display a behavioral and autonomic thermoneutral zone that is surprisingly similar to individual mice. The standard housing T_a of 22 to 24 °C is significantly below the thermoneutral zone of groups of mice suggesting that they are subjected to varying degrees of cold stress under standard housing conditions.

C. Yamauchi, S. Fujita, T. Obara, and T. Ueda*: Effects of Room Temperature on Reproduction, Body and Organ Weights, Food and Water Intake, and Hematology in Mice*, 1983, Exp. Anim., 32:1-11.

Two consecutive generations of mice were raised at graded room temperatures ranging from 12 to 32 °C at intervals of 2 °C. The delivery rate decreased at 30 and 32 °C, and the litter size and weaning rate decreased above 28 °C. No significant difference was demonstrated within the 12 to 26 °C range for any reproduction parameters observed. The body weights of the first-generation mice born at 22 °C did not significantly differ after being transferred to rooms in the 14 to 28 °C range after eight and 16 weeks of exposure. The second-generation mice born and reared at various temperature levels did not show significant intergroup differences in weight within the 20 to 26 °C range at any age in the growth period. No significant intergroup difference was observed within the 20 to 26 °C range with respect to food and water intakes in the second-generation mice. Hematological values and organ weights in the first- and second-generation mice of both sexes did not significantly differ in any parameter within the 20 to 26 °C range. The

results suggest the temperature range of 20 to 26 °C to be optimal for laboratory mouse rooms.

C.Yamauchi, S. Fujita, T. Obara, and T. Ueda: *Effects of Room Temperature on Reproduction, Body and Organ Weights, Food and Water Intake, and Hematology in Rats*, 1981, Lab. Anim. Sci., 31:251-258.

Two generations of rats were raised at animal room temperature ranging from 12 to 32 °C at steps of 2 °C. The body weight of rats born in 22 °C environment and exposed to each temperature did not significantly differ within the range of 16 to 28 °C. The delivery rate, litter size, and weaning rate decreased at 30 °C and 32 °C, and only the weaning rate had a tendency to decrease at 12 °C. No significant difference was demonstrated within the 14 to 28 °C range for any reproduction parameter observed. The body weight of sucklings did not differ at birth within the 12 to 32 °C range; and at three weeks of age, there were no differences within the range of 18 to 28 °C. The body weight gain in both sexes after weaning was generally small when the temperature was below 18 °C or above 30 °C. There were no significant differences in food intake within the 20 to 26 °C range, in water intake within the 12 to 26 °C range, in hematological and serum biochemical values within the 20 to 26 °C range, and in organ weights within the 18 to 28 °C range. Therefore, the range of 20 to 26 °C (68 to 78 °F) was the optimum temperature range in rat rooms.

Poole, S., and J. D. Stephenson: *Body Temperature Regulation and Thermoneutrality in Rats*, 1977, Q.J. Exp. Physiol. Cogn. Med. Sci., 62:143-149.

The zone of minimal metabolic rate for wistar rats was between 28 and 32 °C. At this range of ambient temperatures the rats exhibited low motor activity. The rats were most active at temperatures between 18 and 28 °C.

1.3.3 Literature Search on Rats and Mice Moisture Production

Animals produce heat and moisture from their metabolic processes in consistent, predictable quantities. Moisture is vaporized from (1) the passive loss of the water by diffusion through the skin and through respiration and (2) the active loss of water via sweating, panting, and application of saliva, urine, and other forms of moisture to the fur and skin.

Chongyang Liu: *Indirect Calorimetry Study on Laboratory Rat Metabolism at Various Air Temperatures and Velocities*, University of Illinois at Urbana-Champaign, unpublished thesis 1995, 1996.

The study reported evaporative water loss of 4.82 g H_2O/kg/hr at 20 °C.

P.C. Harrison, G. L. Riskowski, R.G. Magghirang, and J.S. Mckee: *Effect of Diet on Metabolism of Laboratory Rats*, Final Report Submitted to NASA, Department of Animal Science University of Illinois at Urbana-Champaign, 1995.

The study reported a mean evaporative water loss of 5.03 $gH_2O/kg/hr$ at 22°C.

C.J. Gordon: *Relationship Between Preferred Ambient Temperature and Autonomic Thermoregulatory Function in Rats*, Am. J. Physiol., 252:r1130-1137, 1987.

The most prominent effects on evaporative water loss occurred when temperature was elevated above 30 °C for rats. The temperature ranges studied ranged from 14 to 34 °C. He measured values of evaporative water loss of 1.2, 1.5, and 1.8 mg H_2O/mLO_2 at 16, 22, and 30°C, respectively.

Note:

- The difference in the values in the above studies reflects the importance of how the body fluids were handled. Gordon (1987) had a pan filled with oil below the rats to collect all the waste and prevent any of that moisture from getting into the air. The oil in the Liu (1996) study formed only a thin layer over water and may not have been sufficient to stop moisture evaporation from both drinking water spills and body fluids voided into the air.

- Schmidt-Nielsen, gives a value for the albino mouse at "laboratory temperature" of 0.85 mg water per ml oxygen consumed. This is equivalent to 3.06 g water/kg/hr. Schmidt-Nielsen, B. and Schmidt-Nielsen, K. *Pulmonary Water Loss in Desert Rodents*. Am. J. Physiol. 162,31-36, 1950.

M.A. Chappell and D.S. Holsclaw, III: *Effects of Wind on Thermoregulation and Energy Balance in Deer Mice* (Peromyscus Maniculatus), J. Comp. Physiol., B154:619-625, 1984.

In studies of wind effects on deer mice, evaporative water loss at 30 and 35 °C indicated that evaporative water loss increased with increasing temperature, and wind speed from 0.05 to 3.75 m/s had little effect at 30 °C while an increase in air velocity increased moisture production at 35 °C.

T. M. Lin, Y.F. Chem, G.G. Liu, and T.C. Chang: *Studies on Thermoregulation in the Rats*, Proc. Natl. Sci. Counc., ROC, 2:46-52, 1979; D.M. Tennent: *A Study of the Water Losses through the Skin in the Rat*, Am. J. Physiol., 145:436-440, 1946.

Studies of rats and other rodents have found that approximately 50 percent of the passive water loss occurs via diffusion across the skin. Respiratory moisture production is highly affected by changes in body temperature and ambient temperature. An increase in breathing rate was found to elevate evaporative water loss in restrained rats, accounting for as much as 21 percent of the total heat loss at an ambient temperature of 31 °C.

1.3.4 Ammonia and Carbon Dioxide Physiochemical Properties

Ammonia and carbon dioxide are the major gaseous pollutants derived from animals and animal waste within the cage. Below are the physiochemical properties as well as current standards set by American Conference of Governmental Industrial Hygienists for ammonia and carbon dioxide.

Ammonia (NH_3):

Ammonia is a colorless gas with a sharp, intensely irritating odor. It is lighter than air and easily liquefied by pressure, and it is very soluble in water, alcohol, and ether. Physiochemical properties include the following:

Molecular weight:	17.03
Specific gravity:	0.77 at 0 ° F; 0.6819 at boiling point
Boiling point:	-3.5 °C
Freezing point:	-77.7 °C
Vapor pressure:	liquid, 8.5 atmospheres at 20 °C

Henderson and Haggard (1927) record temporary blindness and intolerable irritation from high concentrations. Osmond et al. (1968) describes severe eye damage and irritation of the glottis from exposure at high concentration. Schenker (1967) reports that toxic doses of ammonia acutely affect cerebral energy metabolism and this effect is localized at the base of the brain. Smyth (1956) found 1 ppm detected and identified by 10 subjects. Analysis of data obtained in plant surveys conducted by the Bureau of Industrial Hygiene, Detroit Department of Health, during 1965 to 1970 and *National Institute For Occupational Safety and Health: Criteria For A Recommended Standard Occupational Exposure to Ammonia*, 1974, identifies the limit of detection to be below 5 ppm and the complaint level to be 20 to 25 ppm. *Patty's Industrial Hygiene and Toxicology* (1996) states that the odor threshold is between 5 to 53 ppm. As these last three references show, the actual level of initial odor detection varies significantly.

The American Conference of Governmental Industrial Hygienists recommended a time-weighted average (TWA), threshold limit values (TLV) of 25 ppm (approximately 18 mg/m^3) to protect against irritation to eyes and the respiratory tract and minimize discomfort among workers. It also recommended that the short term exposure limit (STEL), however, be set at 35 ppm (approximately 27 mg/m^3).

Other countries' standards are as follows:

West Germany (1974), Japan, Yugoslavia, 50 ppm; East Germany (1973) 33 ppm; USSR (1976), Sweden (1975), Australia, Belgium, Finland, Hungary, Italy, Netherlands, Poland, Romania, Switzerland, all 25 ppm.

Carbon Dioxide (CO_2):

Carbon dioxide is a colorless, odorless, noncombustible gas. Chemical and physical properties include:

Molecular weight: 44.01
Density: 1.527 (air = 1.0)
Melting point: sublimes at -78.33 °C at 76 torr
Vapor pressure: > 1 atm at 20 °C
Solubility: soluble in water to the extent of 171 ml/100 ml at 0 °C and 76 torr, 88 ml/100 ml at 20 °C, and 36 ml/100 ml at 60 °C. Under higher pressure carbon dioxide is more soluble.

Carbon dioxide when inhaled in elevated concentrations may act to produce mild narcotic effects, stimulation of the respiratory center, and asphyxiation, depending on the concentration present and the duration of exposure. The literature contains a variety of reports on human response at varying concentrations. Deaths have been reported from asphyxiation in workers exposed at high concentrations of carbon dioxide. Winter (1937) found that stimulation of the respiratory center is produced at 50,000 ppm (five percent). Schaefer (1951) reported that submarine personnel exposed continuously at 30,000 ppm were only slightly affected as long as the oxygen content of the air was maintained at normal concentrations (minimal content 18 percent by volume). When the oxygen content was reduced 15 percent to 17 percent, the crew complained of ill effects. The gas is weakly narcotic at 30,000 ppm, giving rise to reduced acuity of hearing and increasing blood pressure and pulse. Above this concentration subjective symptoms occur. Signs of intoxication are produced by a 30-minute exposure at 50,000 ppm. Aero Medical Association: Committee on Aviation Toxicology, Blakiston, New York, (1953) concluded that 7 to 10 percent produces unconsciousness within a few minutes. Flury and Zernik (1931) quote Lehman-Hess as stating that exposure at 5,500 ppm of carbon dioxide for six hours caused no noticeable symptoms.

Based on the long-term exposure studies, even though the majority of references are concerned with studies on physically fit males in confined spaces, the American Conference of Governmental Industrial Hygienists (ACGIH) recommended a TLV-TWA of 5,000 ppm (9,000 mg/m^3) for carbon dioxide. In light of the short-term exposure studies of Sinclair and associates (1969), ACGIH also recommended a STEL of 30,000 ppm (54,000 mg/m^3).

Other countries' standards are as follows:

Australia: 5,000 ppm, STEL 30,000 ppm (1990); Federal Republic of Germany: 5,000 ppm, short-term level 10,000 ppm for 60 minutes, three times per shift (1989); Sweden: 5,000 ppm, 15-minute short-term level 10,000 ppm (1984); United Kingdom: 5,000 ppm, 10-minute STEL 15,000 ppm (1987).

1.4 Project Summary

At project conception, NIH recognized that a comprehensive study of air movement, heat transfer, and contamination dispersal in the macro- and microenvironment in animal facilities could only be undertaken using Computational Fluid Dynamics (CFD). CFD is an advanced three-dimensional mathematical technique that can be used to compute the motion of air, water, or any other gas or liquid. If you were learning fluid dynamics as recently as, say 1960, you would be operating in the "two-approach world" of theory and experiment. However, the advent of the high-speed digital computer combined with the development of accurate numerical algorithms for solving physical problems on these computers has revolutionized the way we study and practice fluid dynamics today. The CFD approach provides a tool with which you can carry out numerical experiments and in this way undertake the comprehensive study envisaged.

It was clear from the beginning that the disadvantage of this approach would be the vast amount of data generated for each and every simulation, compounded by undertaking many simulations. This project presents summaries of these data, in terms of mean cage values or mean values in the scientists' breathing zones, to allow a designer or specifier to identify a satisfactory animal facility configuration.

One of the major advantages of using CFD for such research is the confidence to simulate different configurations knowing that all conditions, except those being varied, remain constant. This makes comparison of CFD simulations much more reliable than comparison of experimental studies, where there is always uncertainty that all conditions are kept the same.

However, it is important that all conditions are understood and correctly specified in the CFD simulation so the results it produces are as accurate as possible. In this study, inputs for the CFD, such as heat dissipation and surface temperature of the mice; in addition to moisture, CO_2, and NH_3 generation rates for mice; needed to be defined. Also the characteristics of the cages under study needed to be understood so an accurate mathematical model of a Microisolator cage could be built. As most of these data were not available from literature, an unprecedented set of experimental measurements was undertaken.

Experimental work was undertaken with an instrumented shoebox cage and Microisolator placed in a wind tunnel. Using different approach velocities, the following were measured:

- Cage air velocities
- Cage ventilation rate
- Cage temperature rise

The measurements were taken for:

- Different cage orientations
- With and without simulated mice
- Different cage configurations and designs
- L/min CO_2 injection rate using infrared analyzers
- 100 mL/min CO_2 injection rate using infrared analyzers
- 100 mL/min SF_6 injection rate using gas chromatography

All combinations of approach velocity and cage configuration were simulated in several hundred CFD simulations with appropriate boundary conditions specified to ensure the CFD model agreed with the measured data. This work is documented in section 4.

A further set of extremely careful experiments was undertaken with outbred female mice of HSD-ICR strain, five per cage on hardwood (Beta chip) shavings as bedding. Three indirect, convective calorimeters were used for this phase of project. Air temperature, velocity, and relative humidity were controlled in each calorimeter. The calorimeters were used to measure mice heat, and CO_2 and NH_3 mass production for different cage humidity conditions. This gave constant CO_2 generation rates but showed that NH_3 generation rose over the 10-day period of the experiments and depended on the relative humidity level. This meant the CFD data needed to be post-processed to reflect a room's performance over a 10-day period.

A third series of experiments were carried out to measure the following factors at several thousand points in an "empty" room using a sampling frequency at each point of 40 Hz.:

- Average velocity
- Minimum velocity
- Maximum velocity
- Turbulence intensity

Further measurement of boundary conditions was carried out in an "occupied" room with racks, cages, and simulated animals. At each point the following were measured:

- Mean air velocity
- Median air velocity
- Turbulence intensity
- Air velocity fluctuation range

- Temperature
- Concentration of CO_2

Using the experimental data to provide boundary conditions, various room and ventilation conditions were simulated by CFD. These included:

- Supply type
- Exhaust number and location
- Supply flow rate
- Use of change station and its location
- Number cages on the racks

In total, 100 variations were simulated and these are detailed in section 2. The results are presented in section 3.

Over 18,000 super computer hours (CRAY equivalent) and 10,000 man-hours were needed to complete the CFD and experimental parts of this project.

It should be noted that these reports use Systems International (S.I.) units, that is kilogram, meter, second, Pascal (1 Newton per square meter), watt (1 joule per second) and degrees Celsius, with approximate conversions to Imperial units displayed for reference only. One exception to this rule is the use of cfm (cubic feet per minute) which is in common use for flow rates.

SECTION II

ANIMAL ROOM VARIATIONS

SECTION II: TABLE OF CONTENTS

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2. ANIMAL ROOM VARIATIONS

2.1 Outline of CFD Baseline Model

A typical Animal Research Facility in terms of overall size, air change rate, rack layout, mouse population, pressurization, and other characteristics was modeled as the baseline model for the CFD simulations. The general features of the room are shown in figure 2.01 and listed below.

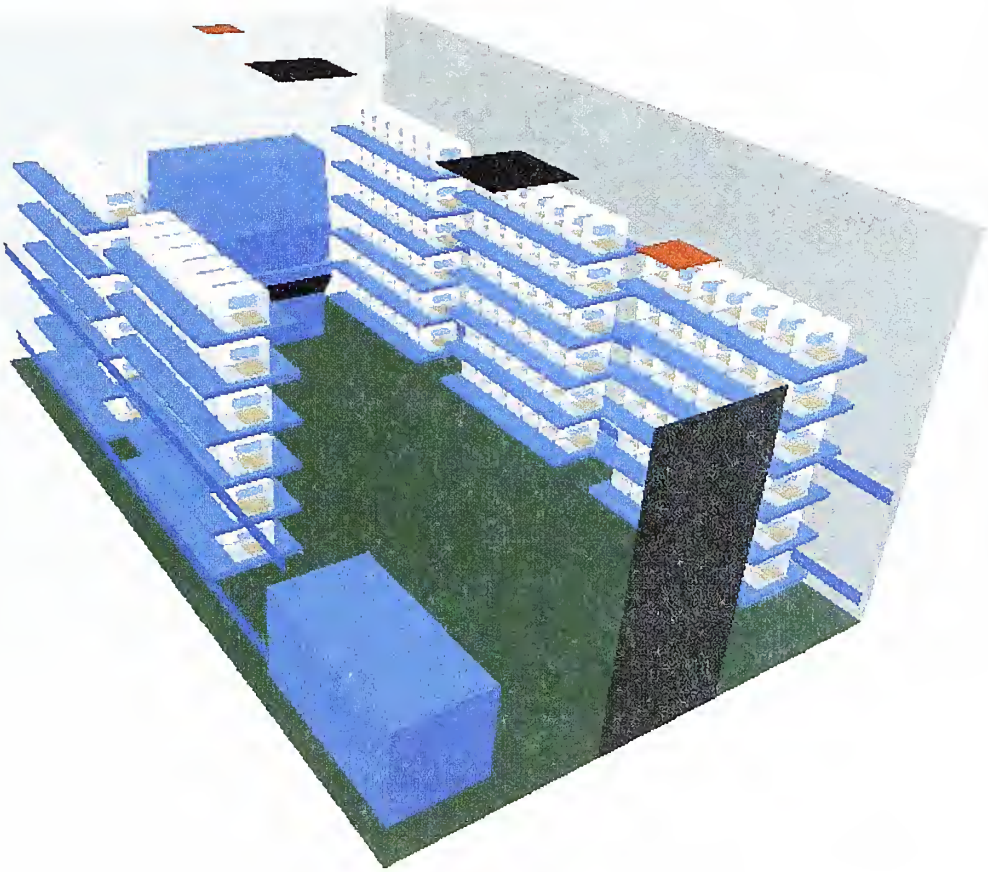

Figure 2.01 *Overall layout of Animal Room Basecase*

Description in brief

The general features of the basecase room model were:

Room: 6.10m x 3.60m x 4.22m (20' 0" x 12' 0" x 9' 0")
Door on short wall
Sink in corner

Laminar flow change station
5 racks

Cages: Microisolator (with filter top) mouse cage
5 mice per cage

Rack: Static system
6 shelves per rack
7 cages per shelf (42 cages per rack)

Supply: 2 radial supplies each providing 270cfm ($0.13m^3/s$) for a total of 15 ACH
Supply discharge temperature, 18.8 °C (66 °F), set such that the exhaust air temperature was 22.2 °C (72.0 °F)
61 percent relative humidity (to provide 50 percent RH at 22.2 °C (72.0 °F)

Exhausts: 2 ceiling level exhausts removing 220 cfm ($0.1m^3/s$) each

Makeup Air: 100cfm ($0.047m^3/s$) coming from around the door

Overall Geometry

In the majority of the cases considered, the animal room occupied a floor area of 6.10m (20' 0") x 3.66m (12' 0"). In some cases considered, the width of the room was increased from 3.66m to 4.22m (14' 0"). The ceiling height in all cases was 2.74m (9' 0"). There was only one door in the room, which was in the center of one of the short walls.

In all the displacement ventilation systems considered in this project, air was introduced through ceiling mounted diffusers. All devices were mounted flush with the ceiling surface; there was no ductwork present within the upper room volume. The various diffuser types considered in this project were all modeled using a combination of several boundary conditions, which were validated previously (see section 4.2.2). All the air exited through general exhausts. The number and locations of the exhausts were varied. In line with common practice, there was an imbalance between the amount of air supplied to the room and the amount exhausted from the room. This leads to an overall pressurization of the room relative to the rooms or corridors surrounding the room. The relative level of pressurization was a parameter considered in this study. The makeup air to compensate for the supply/exhaust imbalance was allowed to enter or leave the room through 6.35e-3m (0.25") gaps on three sides of the door.

The rooms considered in this project all contained five animal cage racks. The rooms also contained one of two alternative design change stations. A fuller description of these items is given below. The only other item within the room was a sink of dimension 0.61m (24") x 0.61m (24") x 0.81m (32") located in one of the corners of the room.

In all cases, the room was considered under dark period conditions, i.e., the lights were off and produced no additional heat load. Dark period conditions were chosen because early experimental work indicated that heat, CO_2, and NH_3 generations were higher in the dark period compared with the lights-on period. Figure 2.02 shows the variation in NH_3 generation over a 10-day period. For CO_2 the generation in the light period was 0.68 g/hr/100g BW compared to 0.91 g/hr/100g BW for the dark period.

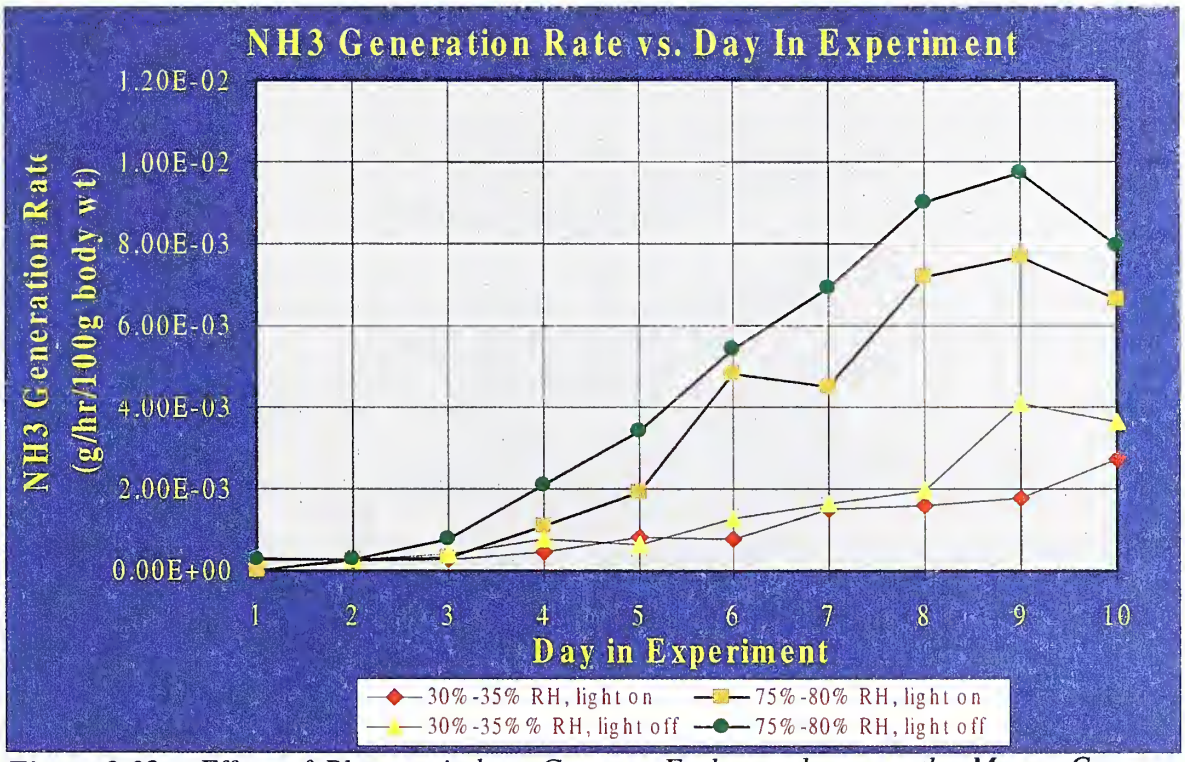

Figure 2.02 *Effect of Photoperiod on Gaseous Exchange between the Mouse Cage and the Room Environment*

Rack Model

The overall dimensions of the rack were 1.52m (60") x 0.61m (24") x 1.83m (72") high, as shown in figure 2.03. There were six shelves in the rack. The spacing of the shelves was 0.32m (12.75") top surface to top surface. The lowest shelf was at a height of 0.21m (8.25") above the floor. The shelves were modeled on thin rectangular blocks. Details such as the connecting ties between the shelves and the rollers on which the racks move, were not modeled, as their effect on the overall flow field and gas concentration distributions was considered insignificant.

Figure 2.03 *CFD Model of Cage Rack*

Located on the shelves of the racks were representations of the animal cages, shown in figure 2.03. The dimensions of the cage were 0.27m (10.7") x 0.16m (6.38") x 0.21m (8.39") high, which maintained the volume of the original cage that had sloped sides. The sides of the cage were modeled as thin plates, with the thickness and conductivity of the plates set to those of the physical cage polycarbonate. The water bottle and food normally found in a cage were modeled as a single block in order to reduce the computational overhead. The volume of the block was the same as that of the bottle and food combined. The bedding of the cage was included as a rectangular block of dimension 0.27m (10.7") x 0.16m (6.38") x 1.27e-2m (0.5").

The mice were modeled as a block of dimension 0.11m (4.25") x 8.57e-2m (3.38") x 0.22m (0.88"). This was the same representation as was used in the experimental cage wind tunnel tests (see section 4.1.1), and simulated the effect of 'huddling' by the mice. The surface temperature of the block was fixed at 30.0 °C (86.0 °F), which was agreed to be a typical mouse body surface temperature.

Surrounding this block a source of CO_2 was defined at 2.12e-7 kg/s (0.76g/hr), which was based on the generation rate indicated for the dark period in the early tests on the effect of the photoperiod on the mice. This source allowed the additional concentration of CO_2 in the air to be calculated in the simulation. The supply air was assumed to have a zero concentration of CO_2. It also allowed the concentration of other species, such as NH_3, to be calculated by scaling, even though it has a different molecular weight than both air and CO_2. This was possible because the magnitude of the source was very small and the resulting concentrations were so low as to have a negligible effect on the density of the mixture of air, CO_2 and NH_3. In effect, the CO_2 and NH_3 are intimately mixed with and flow with the air.

Experimental data later showed the generation rate of CO_2 was actually higher than the source used in the CFD simulations at 0.90 g/hr/100g mouse body weight. This means the concentration of CO_2 in the room and cages was derived from the simulated concentration multiplied by a scaling factor (0.90/0.76). The concentrations of NH_3 in both the cages and the room were also derived by scaling the concentration with a factor specified in the post-processing of the data. This factor was assumed to vary according to two variables: the number of days that passed since the bedding in the cage was changed and the average relative humidity in the cages (see section 4.2.1.2 for the experimental determination of the factors).

Background levels of CO_2 and NH_3 were assumed to be zero. This means that all values quoted in the CFD section of the report are relative to the background level. If an absolute value for CO_2 is required, an additional amount in the range of 300 ppm to 700 ppm for most locations should be added.

The remaining cage boundary conditions are associated with the transfer mechanisms for air/ gases to enter/leave the cage. The cracks at the side of the cage were modeled as 6.35e-3m (0.25") high planar resistances, with the loss coefficient for these resistances having been determined from the cage wind tunnel CFD simulations (see section 4.2.1.2). The top of the cage, which was filtered, was defined as a combination of a planar resistance and a planar source. The determination of the loss coefficient for the resistance and the coefficient for the source has been outlined (see section 4.2.1.1).

The spacing of the cages on the shelves was dependent on whether the racks were single density (seven cages per shelf), or double density (14 cages per shelf). In the single density cases, the cages were centrally located in the short dimension, and equally spaced in the long dimension. The spacing was 4.88e-2m (1.92") from corner of cage to corner of adjacent cage. In the double density racks, the cages were equally spaced in both the long and short dimensions. The spacing was 2.20e-2m (0.87") and 4.88e-2m (1.92") respectively.

Change Station Model

Two alternative change stations were considered in this project. Both stations were constructed primarily from rectangular blocks and triangular prisms. The internal structure and flow field were of no concern in this project. It was only the effect of the station on the room airflow that is of importance.

The first design is shown in figure 2.04 and is based on a Thoren Maximiser. The station had overall dimensions 1.32m (52") x 0.86m (34") x 1.83m (72"). This design was effectively passive in terms of direct flow field interaction. In particular, the station internally recirculated a flow of 350 cfm (1.65e-1 m^3 /s) with only 10 percent leakage defined at the sash opening. The makeup air intake for this leakage was mounted at the side of the station. The station dissipated heat that was expected to affect the rooms overall flow field. In particular, the station contributed a load of 720W to the room. This heat was mostly confined to the lower portion of the station where the motor was located.

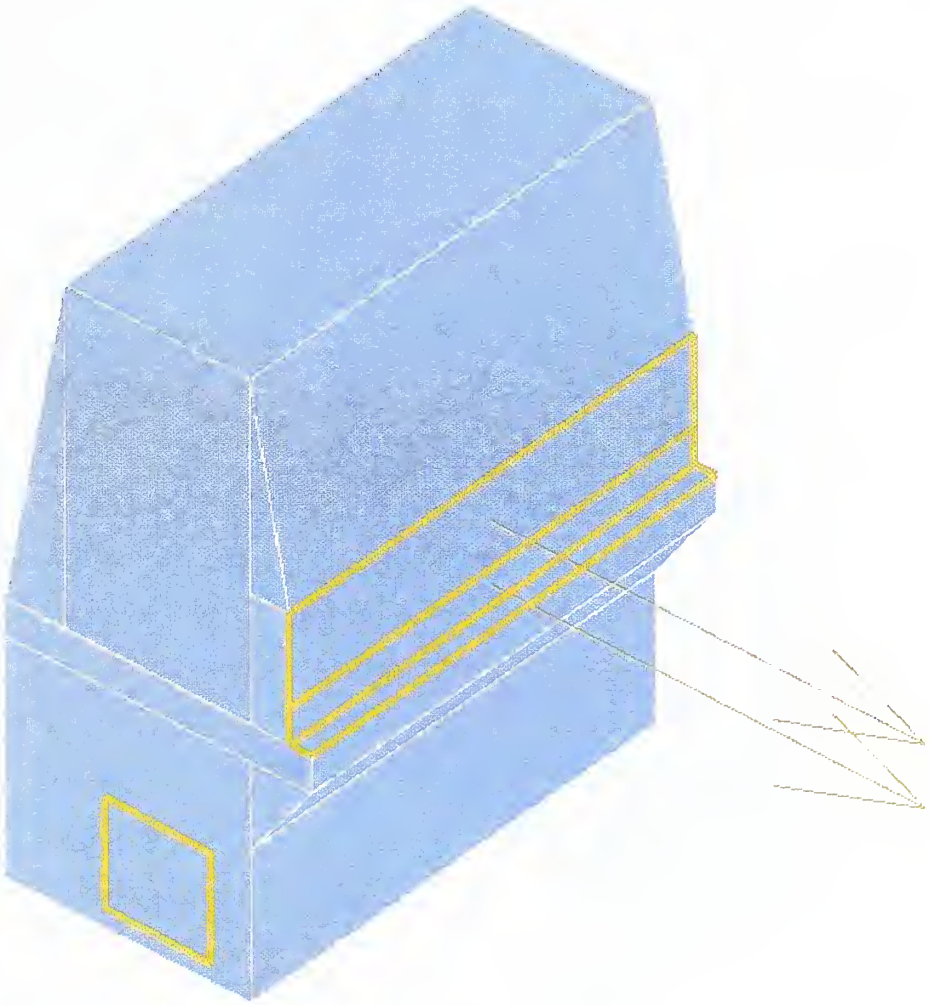

Figure 2.04 *Original Change Station Design*

Due to concerns raised over the relative passiveness of the first station design, a second design was considered, as displayed in figure 2.05 based on a Laboratory Products Stay-Clean Workbench 30909B. The station had overall dimensions 1.50m (59") x 0.86m (34") x 1.93m (76") high. This station also recirculated air, at 300 cfm (1.42e-1 m^3 /s), but discharged a much higher percentage than the first design. In particular, 200 cfm (9.44e-2 m^3/ s) was discharged through grilles at the top of the station. The air makeup to compensate for this discharge was mounted at the front sill at the opening to the station. The station dissipated 660W. This heat was considered to be added to the air discharge at the top of the station.

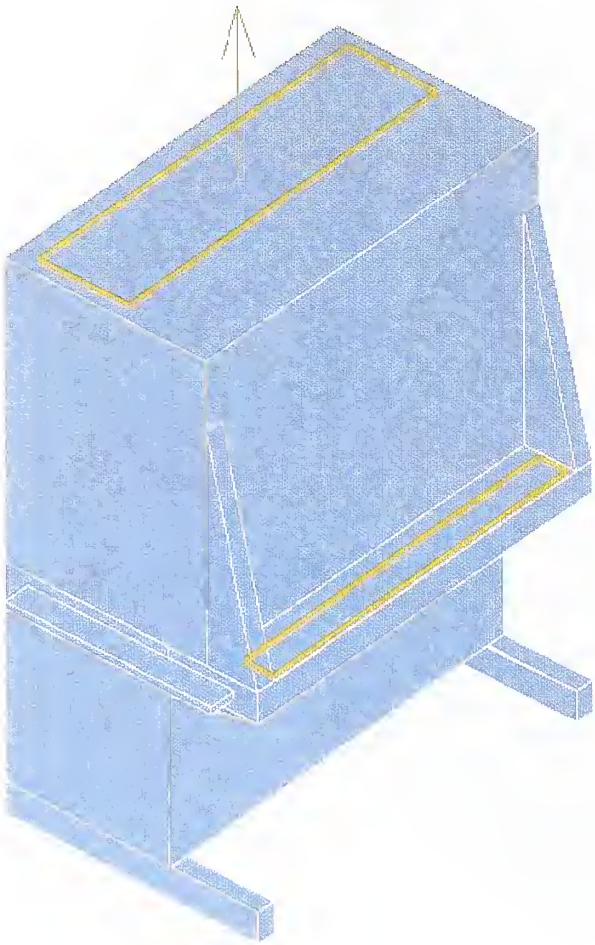

Figure 2.05 Alternative Change Station Design

Modeling Assumptions

- Solar load was not modeled through the walls of the room.
- The floor, ceiling, and walls were assumed to have no heat transfer, i.e., the surrounding areas were assumed to be at the same temperatures.
- All surfaces were treated as smooth when calculating surface friction.

- The sink in the animal room was modeled as a single rectangular block. The recess formed by the shape of the sink was not modeled because the effect of the recess would be negligible on the overall flow field within the room.
- No lighting was assumed in the animal room simulations. The reason for this was that higher CO_2 and NH_3 emissions occur during dark (scotophase) conditions (see figure 2.02, section 4.1.2.8.1 and appendix I: sections 3.4.1.9 and 3.4.1.10).

- The animal room was intended to be kept at a nominal 22.2 °C (72.0 °F). For the simulations the temperature control was assumed to be placed in the exhausts, i.e., the exhaust air temperature was set to be 22.2 °C (72.0 °F), and the supply temperatures were set appropriately.

- No leakage occurred into or out of the animal room other than that specified though the cracks around the door.

- Air density variations due to temperature were negligible. Density variation was therefore ignored in all terms apart from in the momentum term for the vertical velocity component. This is known as the Boussinesq approximation.

- The levels of CO_2 and NH_3 were so diluted in the whole room simulations, even at their source, that the variation of the mixture density due to differing molecular weights was negligible.

2.2 Whole Room Configurations

To investigate a range of parameters, the basic model described in section 2.1 was modified. Wherever possible, only one parameter was varied at a time to fully assess the effect.

The list of room runs as they were considered is given in table 2.01. Parameters considered in this report are:

- *Supply Diffuser Type*: Three different diffuser types were considered in this project: radial diffusers; low induction diffusers; and slot diffusers. While all these diffuser types are ceiling mounted diffusers, the flow patterns resulting from them are fundamentally different (see section 4.2.2). See figures 2.06 to 2.08.

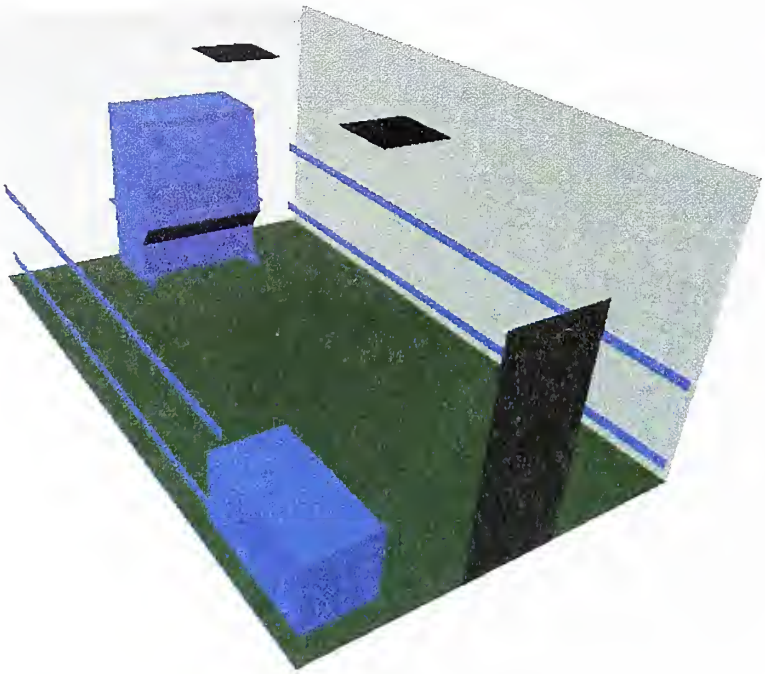

Figure 2.06 *Radial Diffuser*

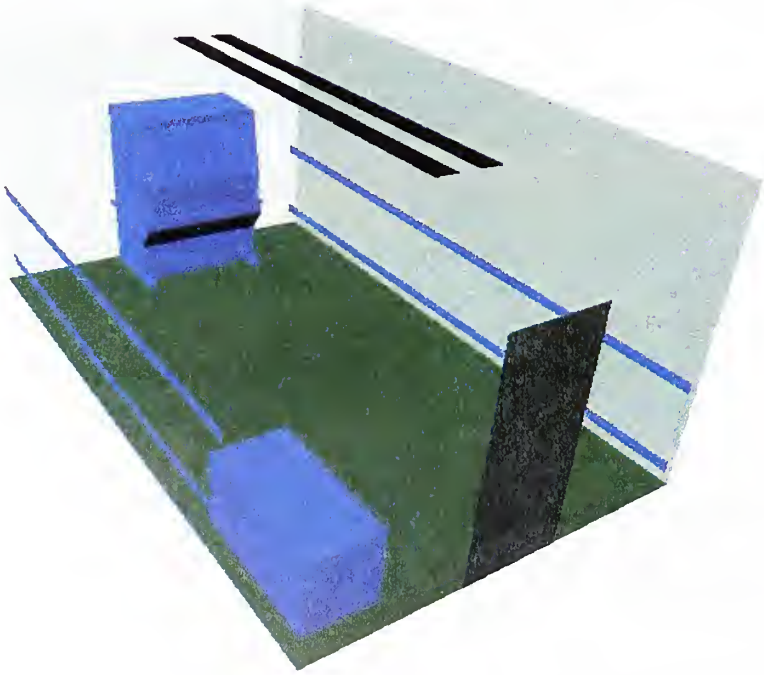

Figure 2.07 *Slot Diffuser*

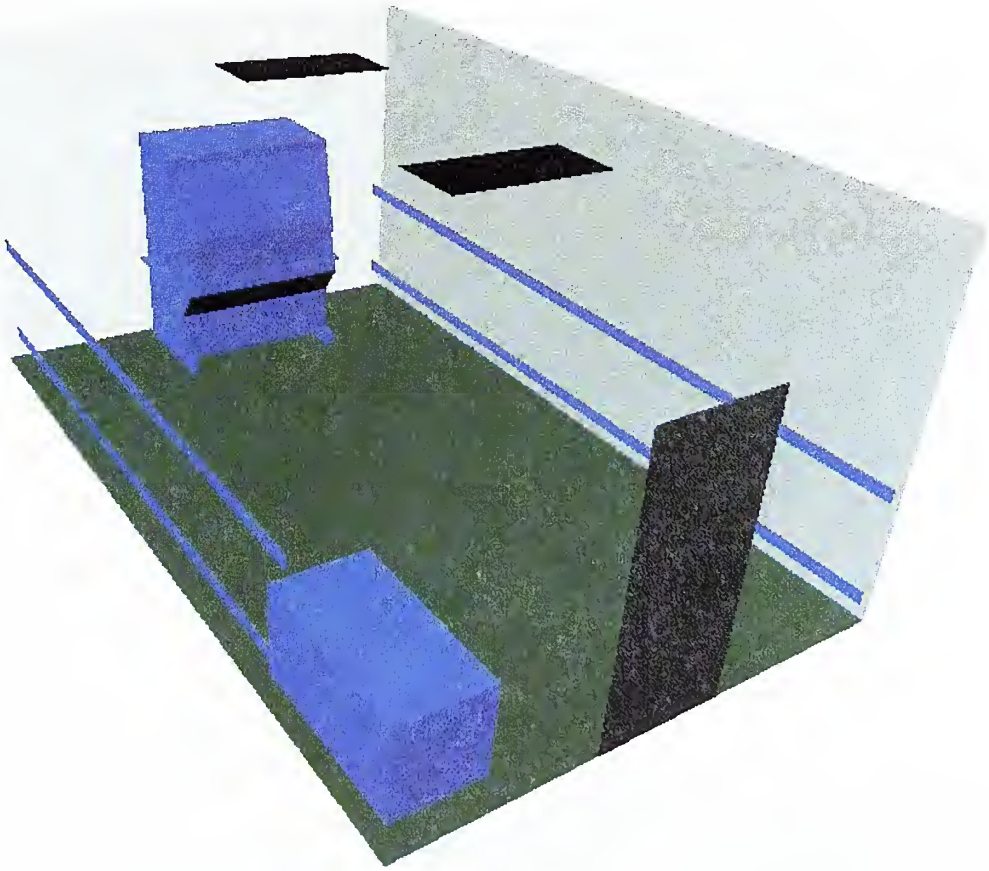

Figure 2.08 *Low Induction Diffuser*

- *Exhaust Location and Number*: Four different exhaust locations were considered, as follows: ceiling, high level, low level on the long walls, and low level on the door wall. The number of exhausts used in each of these locations was also considered as a parameter. See figures 2.09 to 2.12.

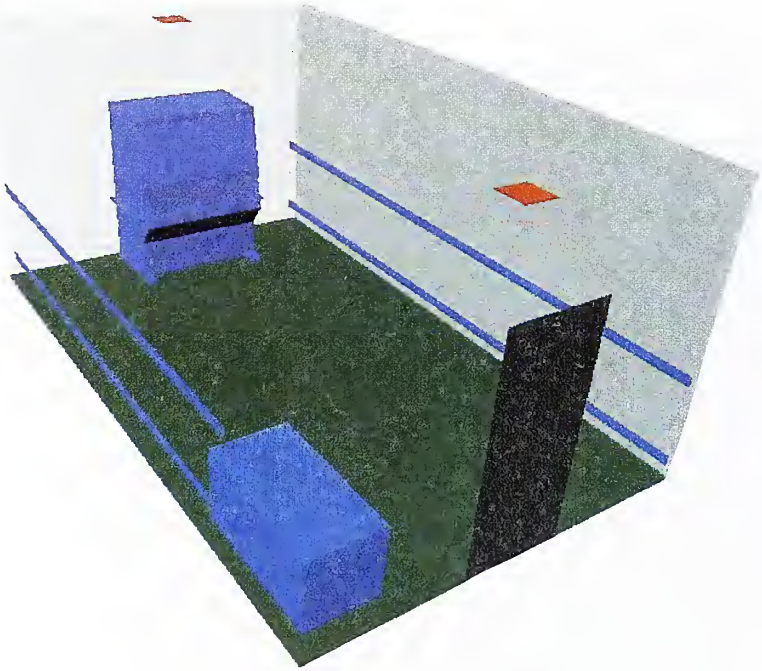

Figure 2.09 *Ceiling Level Exhausts*

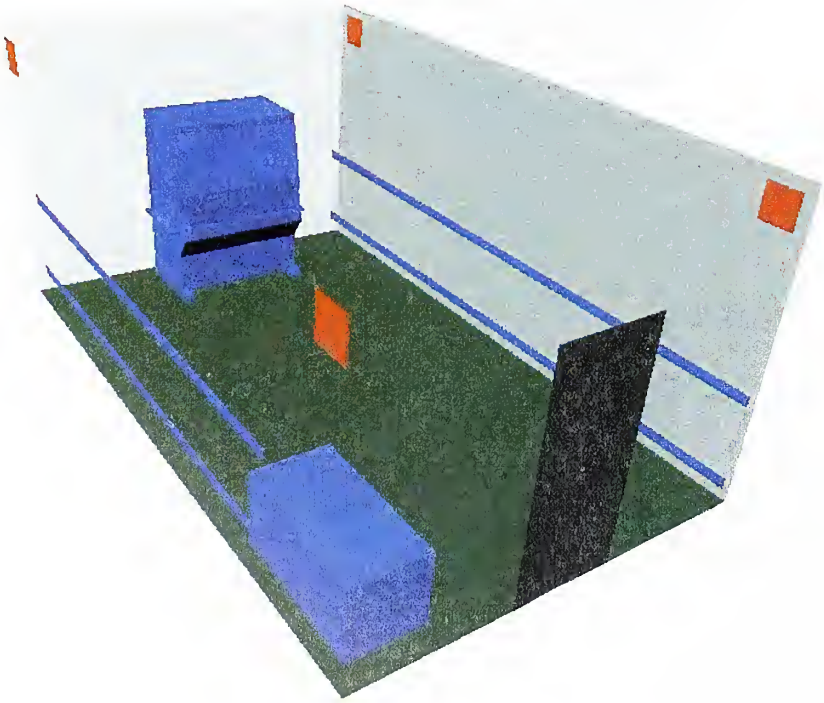

Figure 2.10 *High Level Exhausts*

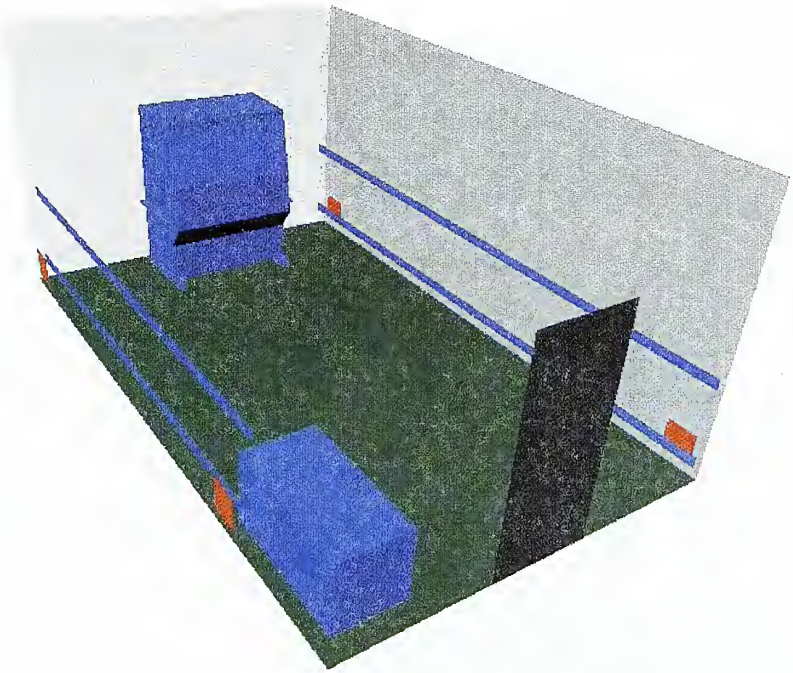

Figure 2.11 *Low Level Exhausts*

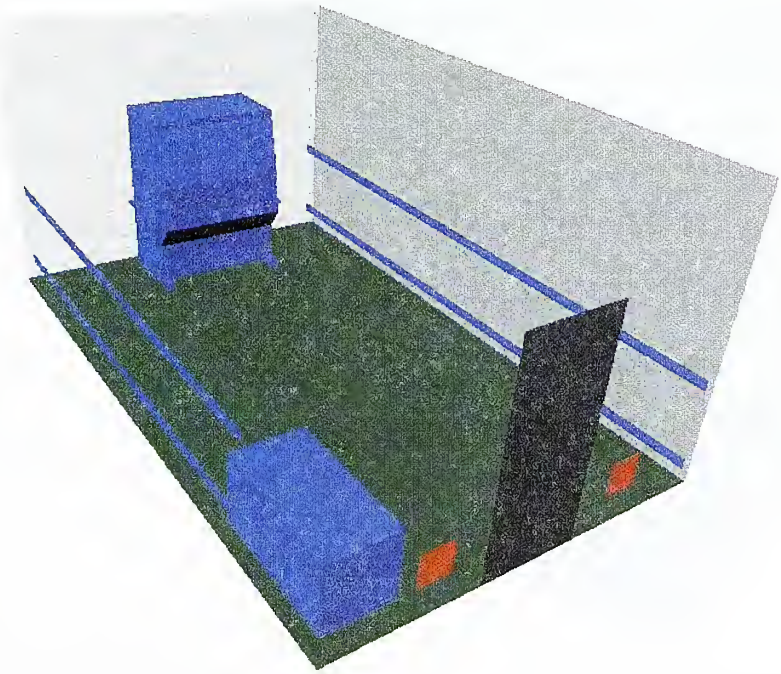

Figure 2.12 *Low Level Exhausts on the Door Wall*

- *Room Air Change Rate*: In addition to the basecase ACH of 15, three other ACH values were considered: 5, 10 and 20 ACH.

- *Change Station Design and Status*: Two different change station designs were considered, as outlined above. The two designs were intended to present both a passive and intrusive influence to the room volume. In the case of the former design, the station was also considered switched off.

- *Pressurization of Room Relative to Corridor*: The pressurization of a room is dependent on the difference between the supply and exhaust flow rates. A higher exhaust rate than supply leads to negative pressurization of the room, and hence makeup air is supplied to the room via available transfer mechanisms (namely door cracks). In this project, the amount of makeup air allowed through the door cracks was varied between 100 cfm (4.72e-1 m^3/s) into the room to 100 cfm (4.72e-1 m^3/s) out of the room.

- *Orientation of Cage Racks in Room*: The racks were considered both parallel to the long walls and perpendicular to them. See figures 2.13 and 2.14.

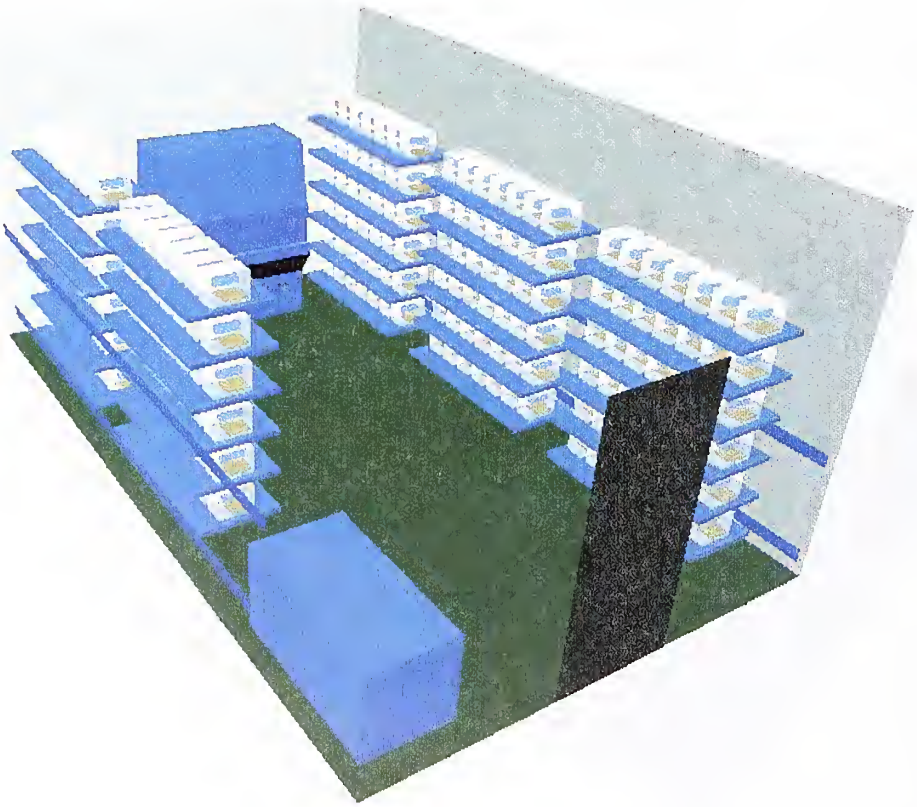

Figure 2.13 *Racks Parallel to Side Walls*

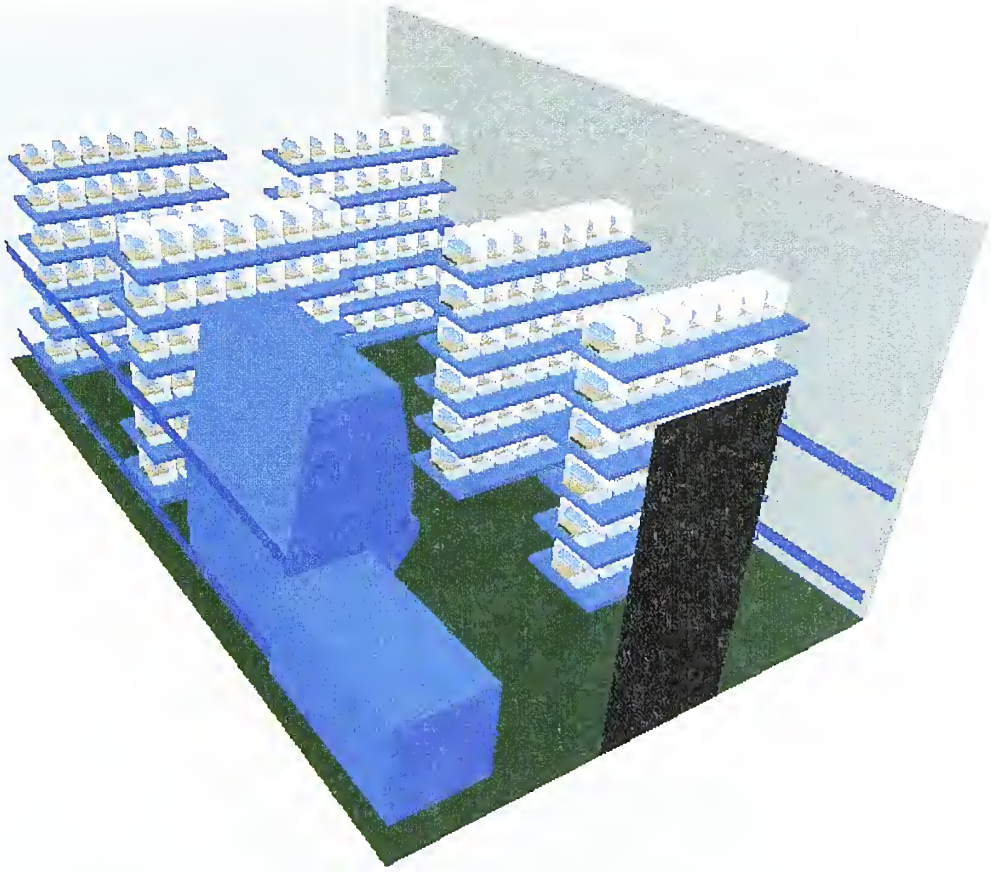

Figure 2.14 *Racks Perpendicular to Side Walls*

- *Side Cracks of Cage Sealed Instead of Open*: A series of cases was considered in which the side cracks of the cage were sealed, leaving the cage filter top as the only transfer mechanism. The main objective here was to establish the relative increase in cage NH_3 and CO_2 levels when the secondary transfer mechanism is removed.

- *Density of Cages*: The number of cages per rack was considered as a parameter. In addition to the basecase value of 42 cages per rack, a double density rack was considered (84 cages per rack), as was a reduced density rack of 28 cages per rack. See figures 2.15 and 2.16.

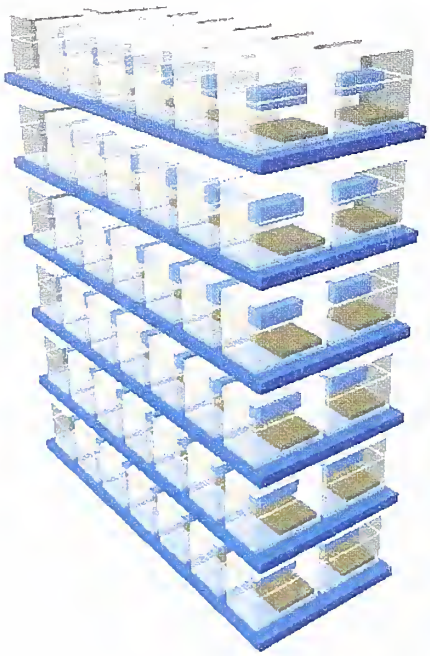

Figure 2.15 *Double Density Rack*

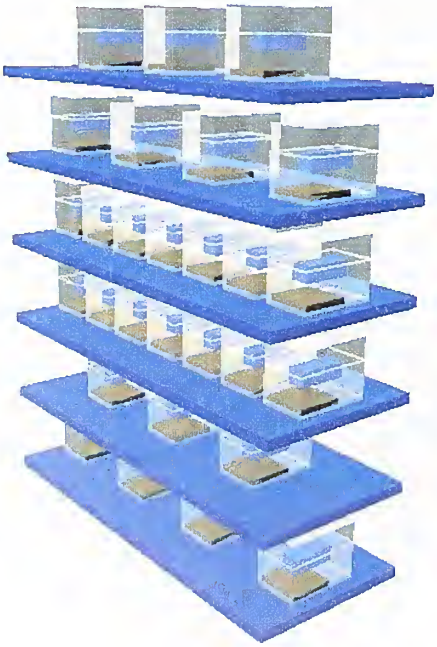

Figure 2.16 *Reduced Density Rack*

- *Location of Change Station*: The location of the change station was considered swapped with each of the racks in the room. See figures 2.17 to 2.21.

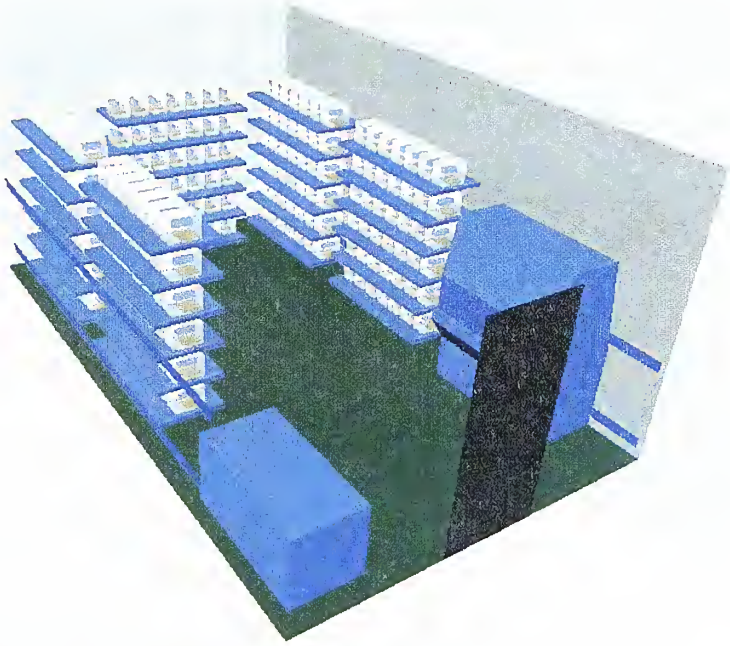

Figure 2.17 *Change Station Swapped with Rack 1*

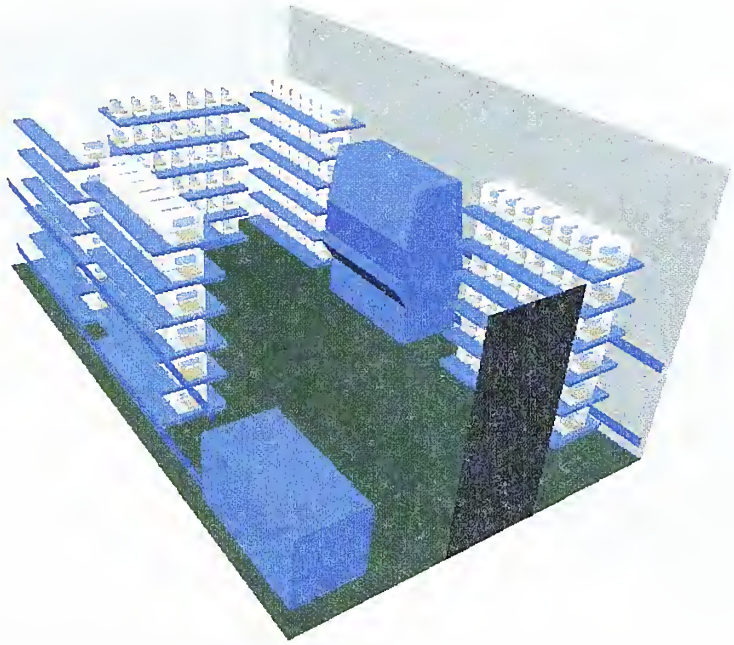

Figure 2.18 *Change Station Swapped with Rack 2*

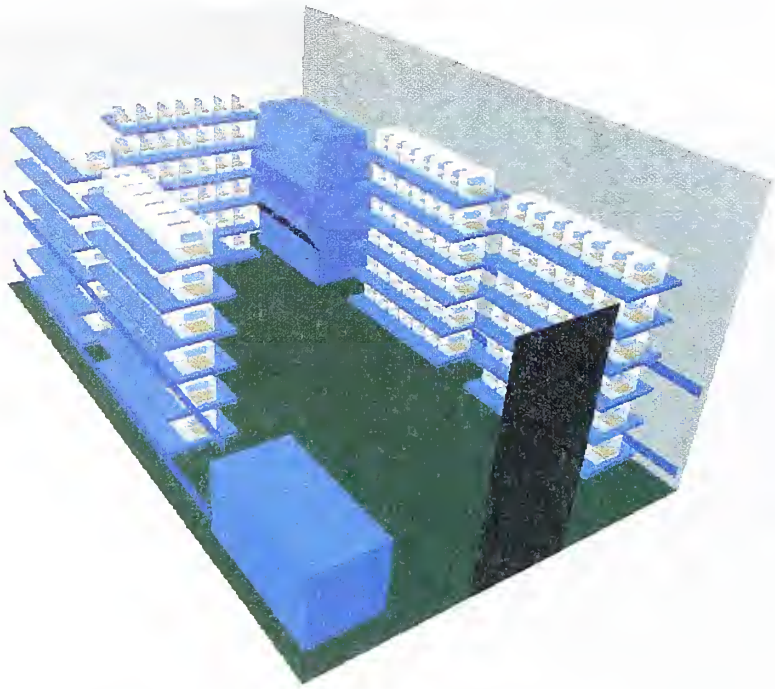

Figure 2.19 *Change Station Swapped with Rack 3*

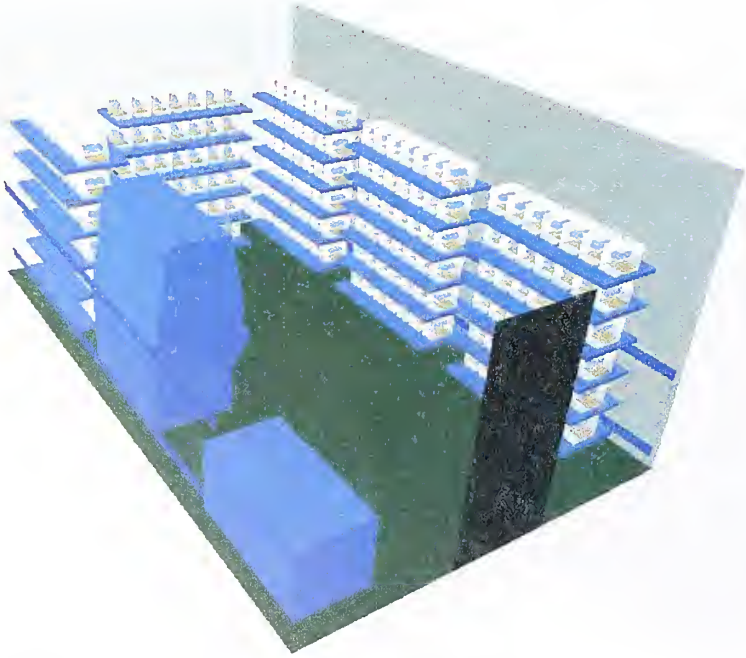

Figure 2.20 *Change Station Swapped with Rack 4*

Figure 2.21 *Change Station swapped with Rack 5*

- *Rack Grouping*: In some series, the racks were considered to be along one wall only, rather than spread out through the room. See figure 2.22.

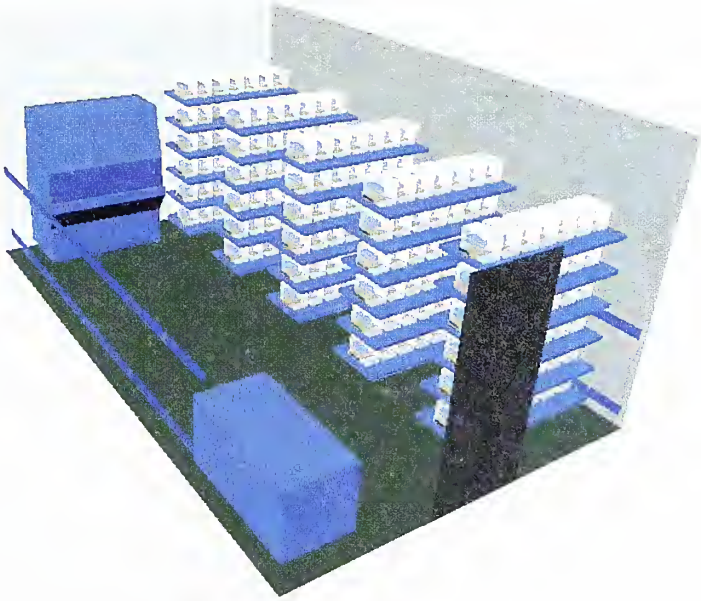

Figure 2.22 *Racks on One Wall Only*

- *Room Width:* Three runs were performed with the room width increased to 4.26m (14' 0").

- *Supply Air Temperature*: In a few runs the supply air temperature was raised to 22.2 °C (72.0 °F) at 49 percent RH, which would cause the room and exhaust temperatures to be about 2 to 3 °C (3.6 to 5.4 °F) higher than the design value of the baseline case.

Table 2.01 List of All Whole Room Runs

Case Name	Supply Diffuser Type	Exhaust Location and Number	Change Station (Design/ Status)	Rack orientation	Rack density	Pressure of Room to Corridor	Supply Temperature °C (°F)	Supply ACH
Basecase	Radial	Ceiling (x2)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 02	Radial	High (x4)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 03	Radial	Low (x4)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 04	Slot	Ceiling (x2)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 05	Slot	High (x4)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 06	Slot	Low (x4)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 07	Low Ind	Ceiling (x2)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 08	Low Ind	High (x4)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 09	Low Ind	Low (x4)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 10	Radial	Ceiling (x2)	Thoren/ OFF	Parallel	Single	Neg. 100cfm	20.7 (69.3)	15
Case 11	Radial	Low (x4)	Thoren/ OFF	Parallel	Single	Neg. 100cfm	20.7 (69.3)	15
Case 12	Slot	Ceiling (x2)	Thoren/ OFF	Parallel	Single	Neg. 100cfm	20.7 (69.3)	15
Case 13	Slot	Low (x4)	Thoren/ OFF	Parallel	Single	Neg. 100cfm	20.7 (69.3)	15
Case 14	Low Ind	Ceiling (x2)	Thoren/ OFF	Parallel	Single	Neg. 100cfm	20.7 (69.3)	15
Case 15	Low Ind	Low (x4)	Thoren/ OFF	Parallel	Single	Neg. 100cfm	20.7 (69.3)	15
Case 16	Radial	Ceiling (x2)	Thoren/ ON	Parallel	Single	Pos. 100cfm	18.8 (65.8)	15
Case 17	Slot	Ceiling (x2)	Thoren/ ON	Parallel	Single	Pos. 100cfm	18.8 (65.8)	15
Case 18	Low Ind	Ceiling (x2)	Thoren/ ON	Parallel	Single	Pos. 100cfm	18.8 (65.8)	15
Case 19	Radial	Ceiling (x2)	Thoren/ ON	Perpendicular	Single	Neg. 100cfm	18.8 (65.8)	15
Case 20	Slot	Ceiling (x2)	Thoren/ ON	Perpendicular	Single	Neg. 100cfm	18.8 (65.8)	15
Case 21	Low Ind	Ceiling (x2)	Thoren/ ON	Perpendicular	Single	Neg. 100cfm	18.8 (65.8)	15
Case 22	Radial	Low (x4)	Thoren/ ON	Perpendicular	Single	Neg. 100cfm	18.8 (65.8)	15
Case 23	Slot	Low (x4)	Thoren/ ON	Perpendicular	Single	Neg. 100cfm	18.8 (65.8)	15
Case 24	Low Ind	Low (x4)	Thoren/ ON	Perpendicular	Single	Neg. 100cfm	18.8 (65.8)	15
Case 25 *	Radial	Ceiling (x2)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 26 *	Slot	Ceiling (x2)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 27 *	Low Ind	Ceiling (x2)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 28	Low Ind	Low (x4)	Thoren/ ON	Parallel	Single	Neg. 100cfm	16.8 (62.2)	10
Case 29	Low Ind	Low (x4)	Thoren/ ON	Parallel	Single	Neg. 100cfm	11.0 (51.8)	5
Case 30	Low Ind	Low (x4)	Thoren/ ON	Parallel	Single	Neg. 100cfm	19.8 (67.6)	20
Case 31	Radial	Low (x4)	Thoren/ ON	Perpendicular	Double	Neg. 100cfm	17.5 (63.5)	15
Case 32	Slot	Low (x4)	Thoren/ ON	Perpendicular	Double	Neg. 100cfm	17.5 (63.5)	15
Case 33	Low Ind	Low (x4)	Thoren/ ON	Perpendicular	Double	Neg. 100cfm	17.5 (63.5)	15
Case 34	Radial	Ceiling (x2)	Thoren/ ON	Perpendicular	Double	Neg. 100cfm	17.5 (63.5)	15
Case 35	Slot	Ceiling (x2)	Thoren/ ON	Perpendicular	Double	Neg. 100cfm	17.5 (63.5)	15
Case 36	Low Ind	Ceiling (x2)	Thoren/ ON	Perpendicular	Double	Neg. 100cfm	17.5 (63.5)	15
Case 37	Radial	Ceiling (x1) / Low (x4) (Mass flow in 50/50 split)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 38	Slot	Ceiling (x1) / Low (x4) (Mass flow in 50/50 split)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 39	Low Ind	Ceiling (x1) / Low (x4) (Mass flow in 50/50 split)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15

Case Name	Supply Diffuser Type	Exhaust Location and Number	Change Station (Design/ Status)	Rack orientation	Rack density	Pressure of Room to Corridor	Supply Temperature °C (°F)	Supply ACH
Case 40	Radial	Ceiling (x4)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 41	Slot	Ceiling (x4)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 42	Low Ind	Ceiling (x4)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 43	Low Ind (rotated by 90°)	Ceiling (x2)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 44	Radial (rotated by 90°)	Ceiling (x2)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 45	Radial	Ceiling (x2)	Thoren/ ON	Parallel	Single	Neg. 50cfm	18.8 (65.8)	15
Case 46	Radial	Ceiling (x2)	Thoren/ ON	Parallel	Single	Neutral	18.8 (65.8)	15
Case 47	Radial	Ceiling (x2)	Thoren/ ON	Parallel	Single	Pos. 50cfm	18.8 (65.8)	15
Case 48	Radial	Ceiling (x2)	Thoren/ ON (swapped with rack1)	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 49	Radial	Ceiling (x2)	Thoren/ ON (swapped with rack2)	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 50	Radial	Ceiling (x2)	Thoren/ ON (swapped with rack3)	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 51	Radial	Ceiling (x2)	Thoren/ ON (swapped with rack4)	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 52	Radial	Ceiling (x2)	Thoren/ ON (swapped with rack5)	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 53	Radial	Ceiling (x2)	Lab. Prod. / ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 54	Slot	Ceiling (x2)	Lab. Prod. / ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 55	Low Ind	Ceiling (x2)	Lab. Prod. / ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 56	Radial	High (x4)	Lab. Prod. / ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 57	Radial	Low (x4)	Lab. Prod. / ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 58	Slot	High (x4)	Lab. Prod. / ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 59	Slot	Low (x4)	Lab. Prod. / ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 60	Low Ind	High (x4)	Lab. Prod. / ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 61	Low Ind	Low (x4)	Lab. Prod. / ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 62	Low Ind	Low (x4)	Thoren/ ON	Perpendicular	Double	Neg. 100cfm	6.6 (43.9)	5
Case 63	Low Ind	Low (x4)	Thoren/ ON	Perpendicular	Double	Neg. 100cfm	14.8 (58.6)	10
Case 64	Low Ind	Low (x4)	Thoren/ ON	Perpendicular	Double	Neg. 100cfm	18.9 (66.0)	20
Case 65	Low Ind	Low (x4)	Lab. Prod. / ON	Perpendicular	Double	Neg. 100cfm	17.5 (63.5)	15
Case 66	Low Ind	Low (x4)	Lab. Prod. / ON	Perpendicular	Double	Neg. 100cfm	6.6 (43.9)	5
Case 67	Low Ind	Low (x4)	Lab. Prod. / ON	Perpendicular	Double	Neg. 100cfm	14.8 (58.6)	10
Case 68	Low Ind	Low (x4)	Lab. Prod. / ON	Perpendicular	Double	Neg. 100cfm	18.9 (66.0)	20

Case Name	Supply Diffuser Type	Exhaust Location and Number	Change Station (Design/ Status)	Rack orientation	Rack density	Pressure of Room to Corridor	Supply Temperature °C (°F)	Supply ACH
Case 69	Radial	High (x4) / Low (x4) (Mass flow split evenly amongst exhausts)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 70	Slot	High (x4) / Low (x4) (Mass flow split evenly amongst exhausts)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 71	Low Ind	High (x4) / Low (x4) (Mass flow split evenly amongst exhausts)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 72	Radial	High (x4) / Low (x2) (Mass flow split evenly amongst exhausts)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 73	Slot	High (x4) / Low (x2) (Mass flow split evenly amongst exhausts)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 74	Low Ind	High (x4) / Low (x2) (Mass flow split evenly amongst exhausts)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 75	Radial	Ceiling (x1) / Low (x4) (Mass flow in 50/50 split)	Lab. Prod. / ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 76 **	Radial	Ceiling (x2)	Thoren/ ON	Parallel	Single	Neg. 100cfm	19.2 (66.6)	15
Case 77 **	Slot	Ceiling (x2)	Thoren/ ON	Parallel	Single	Neg. 100cfm	19.2 (66.5)	15
Case 78 **	Low Ind	Ceiling (x2)	Thoren/ ON	Parallel	Single	Neg. 100cfm	19.2 (66.6)	15
Case 79	Radial	2 Door exhausts	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 80	Slot	2 Door exhausts	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 81	Low Ind	2 Door exhausts	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 82	Radial	2 Door exhausts	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 83	Slot	2 Door exhausts	Thoren/ ON	Perpendicular	Double	Neg. 100cfm	17.5 (63.5)	15
Case 84	Low Ind	2 Door exhausts	Thoren/ ON	Perpendicular	Double	Neg. 100cfm	17.5 (63.5)	15
Case 85	Radial	Low (x4)	Lab. Prod / ON	Perpendicular	Double	Neg. 100cfm	17.5 (63.5)	15
Case 86	Slot	Low (x4)	Lab. Prod./ ON	Perpendicular	Double	Neg. 100cfm	17.5 (63.5)	15

Case Name	Supply Diffuser Type	Exhaust Location and Number	Change Station (Design/ Status)	Rack orientation	Rack density	Pressure of Room to Corridor	Supply Temperature °C (°F)	Supply ACH
Case 87	Radial	Low (x4)	Thoren/ ON	Parallel	Reduced	Neg. 100cfm	19.2 (66.6)	15
Case 88	Slot	Low (x4)	Thoren/ ON	Parallel	Reduced	Neg. 100cfm	19.2 (66.6)	15
Case 89	Low Ind	Low (x4)	Thoren/ ON	Parallel	Reduced	Neg. 100cfm	19.2 (66.6)	15
Case 90	Radial	Ceiling (x2)	Thoren/ ON	Perpendicular all 5 on 1 wall	Single	Neg. 100cfm	18.8 (65.8)	15
Case 91	Slot	Ceiling (x2)	Thoren/ ON	Perpendicular all 5 on 1 wall	Single	Neg. 100cfm	18.8 (65.8)	15
Case 92	Low Ind	Ceiling (x2)	Thoren/ ON	Perpendicular all 5 on 1 wall	Single	Neg. 100cfm	18.8 (65.8)	15
Case 93	Radial	Ceiling (x2)	Thoren/ ON	Perpendicular all 5 on 1 wall	Double	Neg. 100cfm	17.5 (63.5)	15
Case 94	Slot	Ceiling (x2)	Thoren/ ON	Perpendicular all 5 on 1 wall	Double	Neg. 100cfm	17.5 (63.5)	15
Case 95	Low Ind	Ceiling (x2)	Thoren/ ON	Perpendicular all 5 on 1 wall	Double	Neg. 100cfm	17.5 (63.5)	15
Case 96	Radial	Ceiling (x2)	Lab. Prod. / ON	Perpendicular all 5 on 1 wall	Double	Neg. 100cfm	17.5 (63.5)	15
Case 97	Slot	Ceiling (x2)	Lab. Prod. / ON	Perpendicular all 5 on 1 wall	Double	Neg. 100cfm	17.5 (63.5)	15
Case 98	Low Ind	Ceiling (x2)	Lab. Prod. / ON	Perpendicular all 5 on 1 wall	Double	Neg. 100cfm	17.5 (63.5)	15
Case 99 ***	Radial	Ceiling (x2)	Thoren/ ON	Parallel	Single	Neg. 100cfm	22.2 (72.0)	15
Case 100 ***	Radial	Low (x4)	Thoren/ ON	Parallel	Single	Neg. 100cfm	22.2 (72.0)	15
Case 101 ***	Low Ind	Low (x4)	Lab. Prod. / ON	Perpendicular	Double	Neg. 100cfm	22.2 (72.0)	5

* Sealed cages instead of open cages

** Room 4.26m (14' 0") wide instead of 3.66m (12' 0")

*** Supply air temperature fixed at 22.2 °C (72.0 °F). In all other cases, the exhaust temperature was set to be 22.2 °C (72.0 °F) by setting the supply air temperature appropriately.

Table 2.02 Cases Cross-Referenced against Supply Diffuser Type

Supply Diffuser Type	Case Number
Radial	Basecase, 02-03, 10-11, 16, 19, 22, 25, 31, 34, 37, 40, 44*, 45-53, 56-57, 69, 72, 75-76, 79, 82, 85, 87, 90, 93, 96, 99-100
Slot	04-06,12-13, 17, 20, 23, 26, 32, 35, 38, 41, 54, 58-59, 70, 73, 77, 80, 83, 86, 88, 91, 94, 97
Low Induction	07-09, 14-15, 18, 21, 24, 27-30, 33, 36, 39, 42, 43*, 55, 60-68, 71, 74, 78, 81, 84, 89, 92, 95, 98, 101

*Indicates that diffuser rotated by 90°

Table 2.03 Cases Cross-Referenced against Exhaust Location and Number

Exhaust Location and Number	Case Number
Ceiling (x2)	Basecase, 04, 07, 10, 12, 14, 16-21, 25-27, 34-36, 43-55, 76-78, 90-99
High (x4)	02, 05, 08, 56, 58, 60
Low (x4)	03, 06, 09, 11, 13, 15, 22-24, 28-33, 57, 59, 61-68, 85-89, 100-101
Ceiling (x1) / Low (x4) (Mass flow in 50/50 split)	37-39, 75
Ceiling (x4)	40-42
High (x4)/ Low (x4) (Mass flow split evenly amongst exhausts)	69-71
High (x4)/ Low (x2) (Mass flow split evenly amongst exhausts)	72-74
2 Door Exhausts	79-84

Table 2.04 Cases Cross-Referenced against Change Station Design and Status

Change Station	Case Number
ON*	Basecase – 09, 16-101
OFF*	10-15
Thoren Design	Basecase –52**, 62-64, 69-74, 76-84, 87-95, 99-100
Laboratory Products Design	53-61, 65-68, 75, 85-86, 96-98, 101

* Change in status only considered for Thoren Design Change Station
** Cases 10 to 15 had Thoren Design Change Station switched off

Table 2.05 Cases Cross-Referenced against Pressurization of Room Relative to Corridor

Pressurization of Room to Corridor	Case Number
Neg. 100 cfm	Basecase –15, 19-44, 48-101
Pos. 100 cfm	16-18
Neg. 50 cfm	45
Neutral	46
Pos. 50 cfm	47

Table 2.06 Cases Cross-Referenced against Pressurization of Room Relative to Corridor

Rack Orientation	Case Number
Parallel	Basecase – 18, 25-30, 37-61***, 69-82, 87-89, 99-100
Perpendicular	19-24, 31-36, 62-68, 83-86,101
Perpendicular All 5 on 1 Wall	90-98

***Cases 48 to 52 had change stations swapped with each of five racks

Table 2.07 Cases Cross-Referenced against Status of Cage Side Cracks

Status of Cage Side Cracks	Case Number
Open	Basecase – 24, 28-101
Sealed	25-27

Table 2.08 Cases Cross-Referenced against Density of Cages in Rack

Density of Cages in Rack	Case Number
Single	Basecase – 30, 37-61, 69-82, 90-92, 99-100
Double	31-36, 62-68, 83-86, 93-98, 101
Reduced	87-89

Table 2.09 Cases Cross-Referenced against Room Air Change Rate

Room Air Change Rate (ACH)	Case Number
5	29, 62, 66, 101
10	28, 63, 67
15	Basecase – 27, 31-61, 65, 69-100
20	30, 64, 68

Table 2.10 Cases Cross-Referenced against Room Width

Room Width (ft)	Case Number
12	Basecase-75, 79-101
14	76-78

Table 2.11 Cases Cross-Referenced against Supply Temperature (1)

Supply Temperature	Case Number
Supply Temperature set such that air is at 22.22°C (72°F) at Exhaust	Basecase – 98
22.22°C	99-101

Table 2.12 Cases Cross-Referenced against Supply Temperature (2)

Supply Temperature	Case Number
6.60	62, 66
11.00	29
14.80	63, 67
16.80	28
17.50	31-36, 65, 83-86,93-98
18.80	Basecase – 09, 16-27, 37-61, 69-75, 79-82, 90-92
18.90	64, 68
19.20	76-78, 87-89
19.80	30
20.70	10-15
22.22****	99-101

****In these cases, the supply air temperature was set to 22.22 °C (72 °F). In all other cases, the exhaust air temperature was set to be 22.22 °C (72 °F) by setting supply air temperature appropriately.

2.3 How the Data are Presented

This section presents the outcome of the CFD simulations. There are a number of ways of presenting the results produced with the CFD models. These can be either based upon visualization of the CFD results files or based upon automated analysis of the data contained within those files. The former provides a qualitative approach and can be useful to understand the flow patterns produced within the rooms. The latter provides quantitative measurements of mean values for temperature, CO_2, and NH_3 concentrations and the relative humidity in the cages and the room.

2.3.1 Visualizing the Flow–A Qualitative Approach

Three approaches are used to display the CFD results directly. Two of these show the data in selected planes (planar slices) while the third provides a view in a three-dimensional visualization of the flow of selected air stream.

2.3.1.1 Using planar slices through the model

The results can be displayed in diagrammatic form, e.g., figure 2.23 showing the concentration of CO_2 (kg CO_2/kg air) as a solid color fill and figure 2.24 showing air speed (m/s) as velocity vectors showing both direction as well as magnitude of the airflow. Values for both can be obtained from the color bar (key) in each diagram. The left key is the air speed in m/s (0.1 m/s is equivalent to 20 fpm) and the right key is the mass fraction of CO_2 in g (species)/kg air.

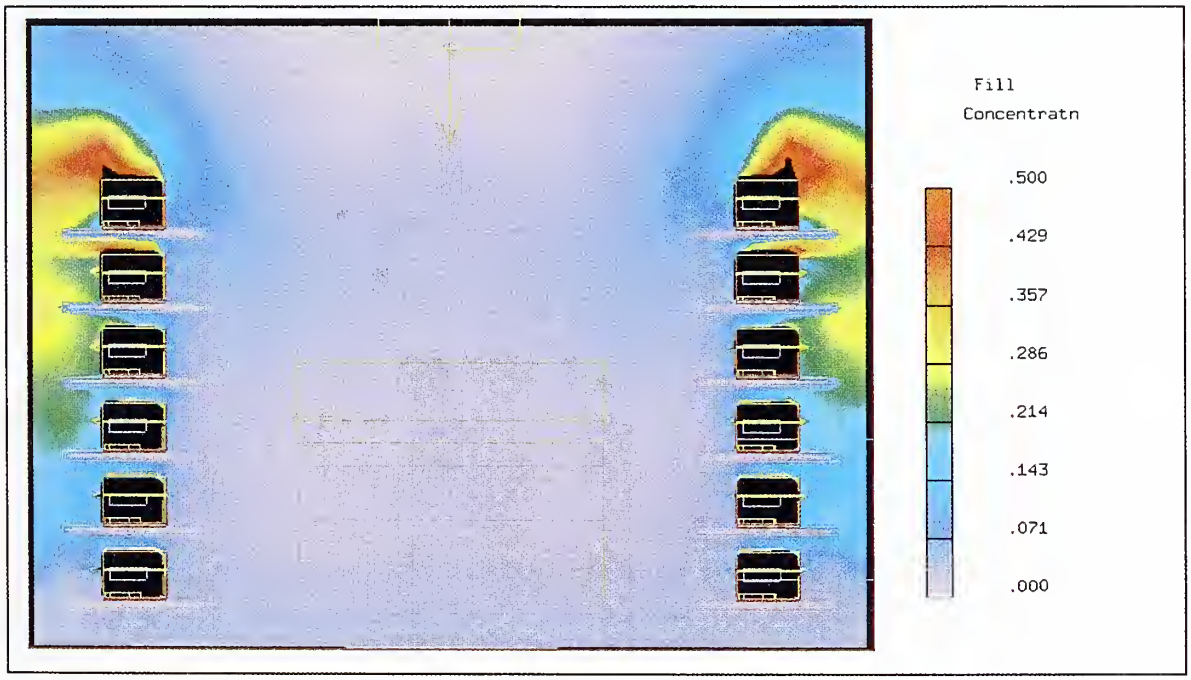

Figure 2.23 *Concentration (CO_2) Distribution (g/kg)*

The CFD simulations were only solved directly for the concentration of CO_2. Concentrations of NH_3 are calculated in the post-processing stage of the quantitative analysis using a factor derived from the relative generation of CO_2 and NH_3. This factor varies according to the relative humidity in the cages and the number of days that have elapsed since the cage bedding was changed.

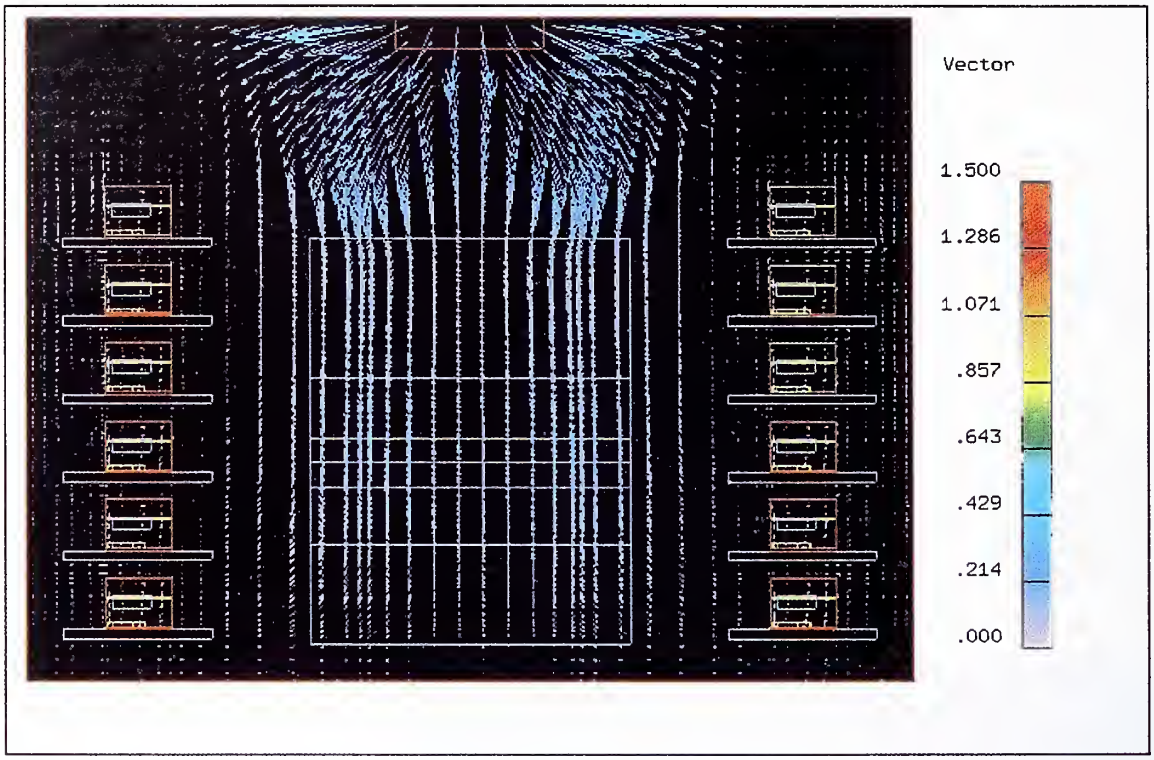

Figure 2.24 Velocity Vectors (m/s)

The vectors are plotted so that the tail of the arrow is at the point where the value was calculated and points in the direction of air movement. In 2-D planar views the length of the arrow indicates the 2-D magnitude of the velocity (the arrow is projected onto the plane of viewing) when compared to a reference vector, while the color indicates the overall magnitude of air speed at the tail.

To aid analysis, the color scales are set the same on different diagrams as much as possible. For example, the temperature scale runs from 18.0 °C to 25 °C (64.4 °F to 77.0 °F). The concentration scale runs from 0.0 to 5 g/kg or from 0.0 to 0.5g/kg depending on whether the plane is concerned with showing the concentrations inside the cages or outside in the room, where the concentrations are generally much lower. Values outside the range will appear as blank areas in the solid fill or a region with no vectors. If lower than the scale, the area is surrounded by colors at the bottom of the range and above by colors at the top of the range.

The vectors show the radial pattern of flow leaving the radial diffuser supply and the strong down flow in the center of the room. The airflow over the cages is very low in this view, as the velocity vectors are very small, appearing virtually as dots. The concentration plot shows high concentrations around the cages at the top of the racks. Even though the velocities are very low around the cages, the tendency for the flow to go over the cages towards the rear wall is clearly evident in the way the concentration levels are much higher behind the cages than in the center of the room.

2.3.1.2 Using three-dimensional flow visualization

Three-dimensional flow visualization allows us to understand the interaction of complex flows. Figure 2.25 shows the airflow from the radial supply in the baseline model. The air is colored according to the temperature of the air, blue through green, yellow and red representing low to high temperatures. Various recirculation regions are visible as the air follows a very complex path from the white supply down the middle of the room and back up to the red exhaust, which is also situated on the ceiling.

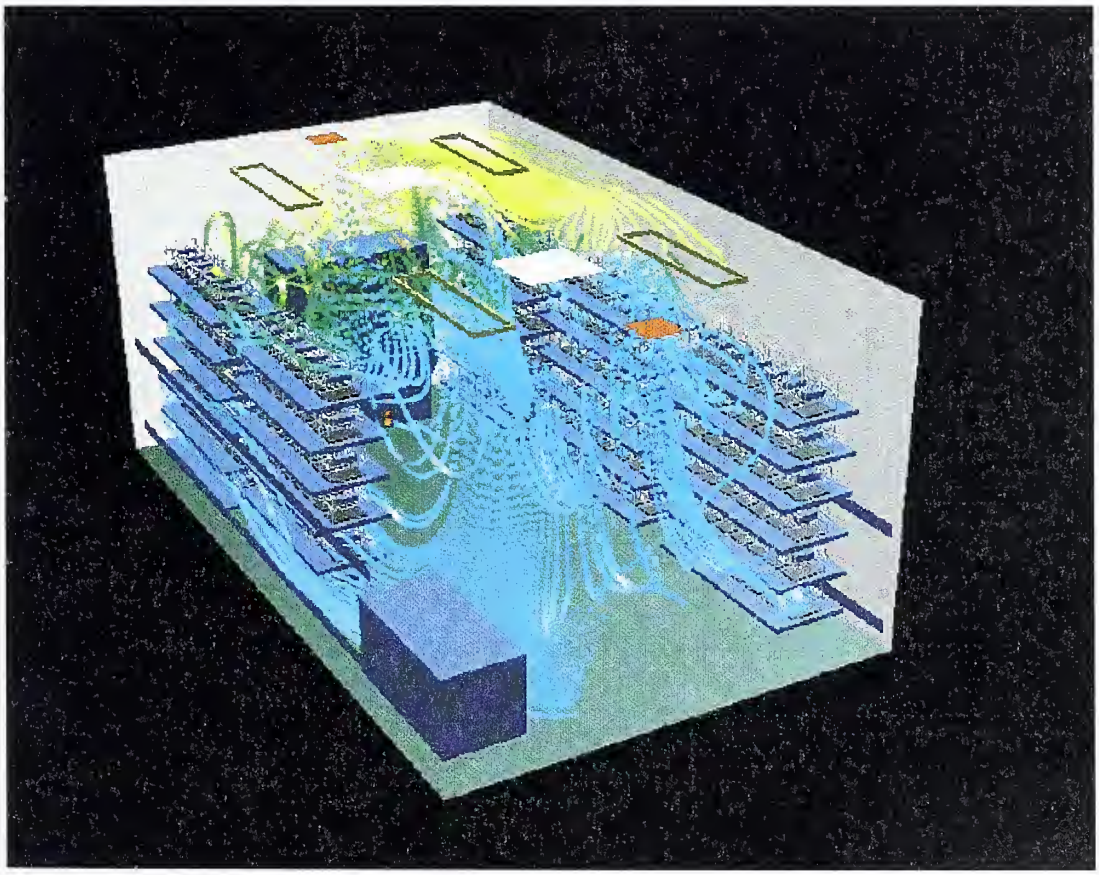

Figure 2.25 *3-Dimension Flow Visualization*

2.3.2 *Quantitative Analysis*

Although visual inspection of the CFD results can give much insight into the conditions within a room, it does not allow an efficient comparison of one room simulation to another. In order to allow us to compare the various room models it was necessary to define some quantitative measures for the cages and the room as a whole. The following parameters were considered important in this study:

Cages:

- Mean temperature in each cage
- Mean relative humidity in each cage
- Mean CO_2 and NH_3 concentrations in each cage

The mean value for each cage was also further averaged to provide a single value representing the "average cage" in the room. These values were calculated for the "occupied zone" of each cage, i.e., the region below the wire mesh grille, which represents the environment the mice would normally experience.

Room:

- Mean breathing zone temperature
- Mean breathing zone relative humidity
- Mean breathing zone CO_2 and NH_3 concentrations

The breathing zone is defined as a region in the center of the room between the racks of cages and between the door and change station, at a height from 1.50m to 1.80m (4'11" to 5'11").

These parameters were derived from the many millions of numbers produced by the CFD simulations as follows:

Temperature:

> The mean temperature was derived from the actual temperature in each grid cell of the CFD simulation by multiplying the temperature by the volume of the grid cell and dividing by the total volume of the space (the cage volume or the "breathing zone" volume in the room).

Relative Humidity:

> The relative humidity was calculated by first determining the moisture content in each cage by taking the mass fraction values calculated in the CFD and multiplying by the ratio of the experimentally determined moisture generation rate (0.83 g/hr) to the nominal

source rate (0.76g/hr). This additional water content was then added to the moisture in the supply air (8.40e-3 kg water per kg air, 50 percent RH at 22.2 °C (72.0 °F) for all cases except those at very low (5 ACH) air supply rates where 5.40e-3 kg/kg was used. The RH can be determined from a Psychrometric chart from the total moisture content of the air and the temperature of the cage

CO_2 (ppm):

The ppm concentrations for CO_2 in air were calculated directly from the simulated mass fraction information in the CFD results by multiplying the mass fraction value by the ratio of the actual generation rate to the nominal generation rate (0.9 / 0.76) and the ratio of molecular weights (29/44).

NH_3 (ppm):

The concentration of NH_3 was also derived from the mass fraction values calculated in the CFD simulations, but the process was more complicated. First, the relative humidity in every cage is calculated as described above. The average RH for all the cages was then used to calculate the generation rate of NH_3 for each day in the 10-day cycle using the experimental data shown in section 4.1.2.8.2. RH values below the minimum range (61 percent) for the experimental data used the generation rate of the minimum value. RH values above the maximum range (81 percent) used the generation rate of the maximum value as it was deemed unsafe to extrapolate outside the ranges. Once the generation rate to be used was determined, the ppm concentration of NH_3 was calculated in the same manner as the CO_2 concentrations.

As each day had a different NH_3 generation rate, the NH_3 concentrations are different on each day. However as the underlying mass fraction information and RH information does not change on a daily basis in the simulations, room performance can be compared by using the results for any of the 10 days. For ease of comparison, results are presented for day 4, which corresponds to the day most widely used to change the bedding in the mice cages.

In addition to the mean values it is also possible to get minimum and maximum values. In most cases the minimum value is not interesting but the maximum value may provide information. In particular, the maximum NH_3 concentration can be important, as it is not always necessary for the room average value to be so high that the scientists can detect it by smell. A high value in a single location could be enough.

The results for each room are summarized in Volume II.

2.3.3 Analysis of the Results for the Baseline Room

Due to the enormous amount of data generated in the CFD runs it is not possible to discuss in detail the results of each case. Initially, this section will look at the flow patterns and the quantitative results generated in the baseline case as this will give a basic understanding of the animal room airflows. Subsequent sections will then compare results for the various room configurations without necessarily discussing each room.

The basecase (case 01) had two radial supply diffusers (supplying 540 cfm at 18.8 °C (66.0 °F)) and two ceiling mounted exhausts. Five racks of 42 cages are placed along to the side walls. See figure 2.02.

Figures 2.26 to 2.28 show velocity vectors, temperature distribution, and CO_2 distribution in a planar section down the center line of the room. The two supplies, with downward facing vectors, and the two exhausts are clearly visible on the ceiling. The inflow of makeup air coming from the cracks around the door is also obvious. The change station generates high temperatures in its vicinity, which causes a strong upward flow of air. This flow causes the downward flow from the supplies to be deflected away from the change station towards the door. The concentration plot shows little variation in CO_2 concentration apart from some small regions behind the change station and very near the ceiling.

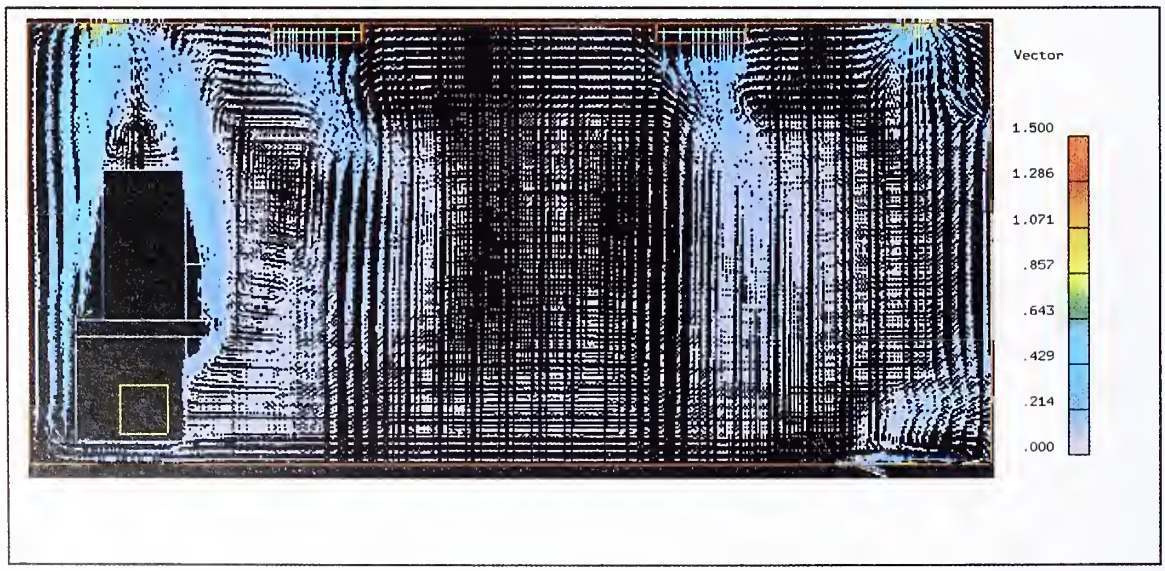

Figure 2.26 Basecase (Case 01): Velocity Vectors

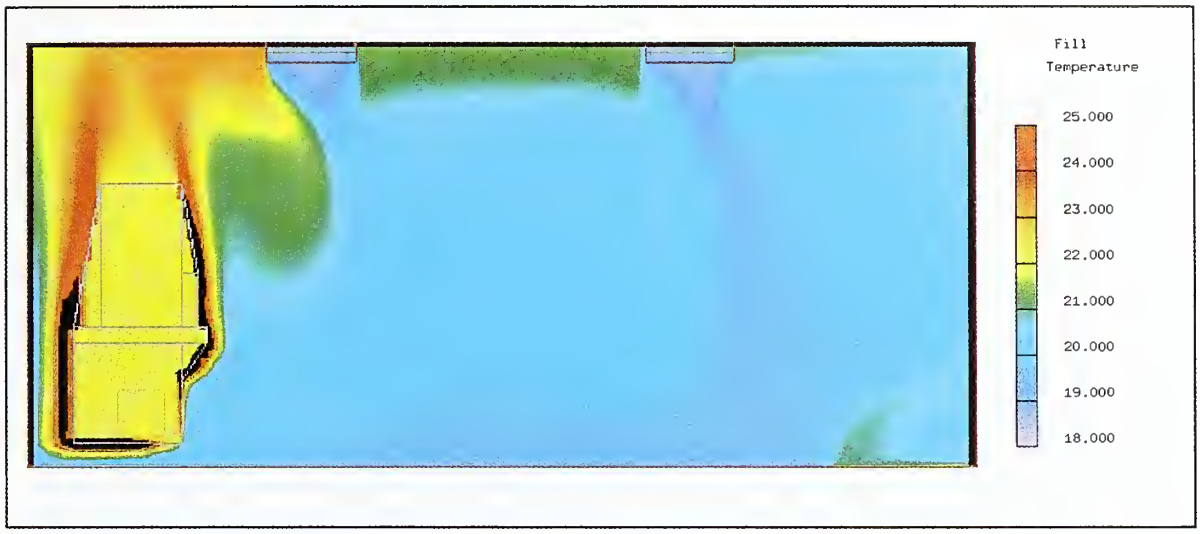

Figure 2.27 *Basecase (Case 01): Temperature Distribution (^oC)*

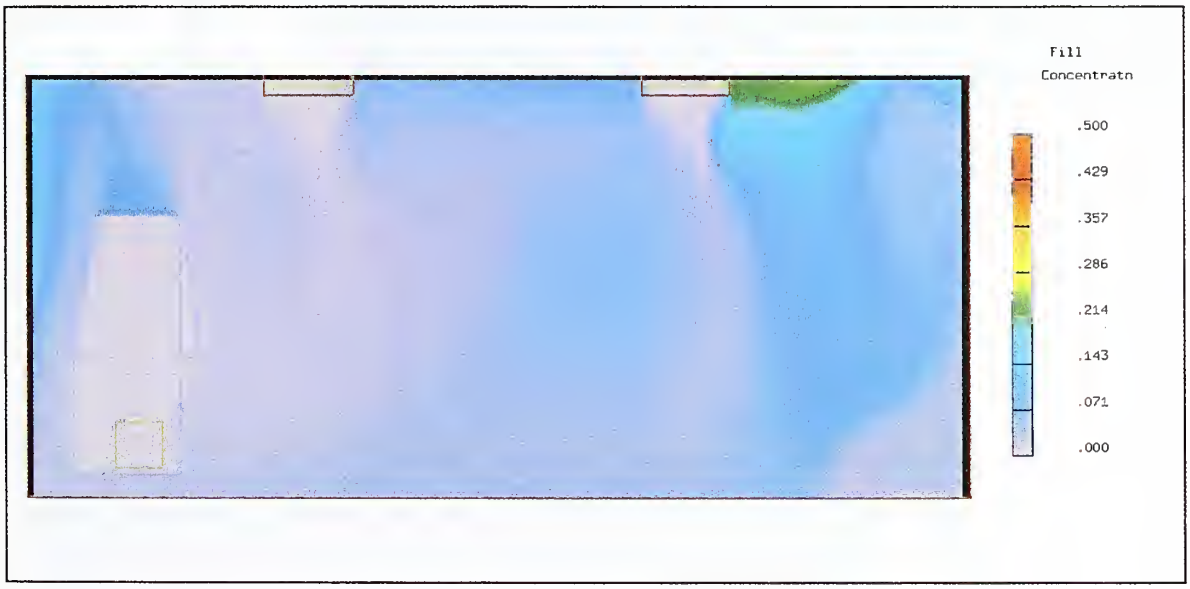

Figure 2.28 *Basecase (Case 01): CO_2 Concentration Distribution (g/kg)*

Figures 2.29 to 2.31 show velocity vectors, temperature distribution, and CO_2 distribution in a planar section cutting through the center of the supply nearest the change station. The characteristic pattern of the flow from the supply is visible, as is the low flow around the cages. The temperature in the room shows signs of stratification with significantly higher temperatures

near the ceiling. The temperature of the cages is higher than that of the surrounding room air, and rises according to the height of the shelf on which the cage sits.

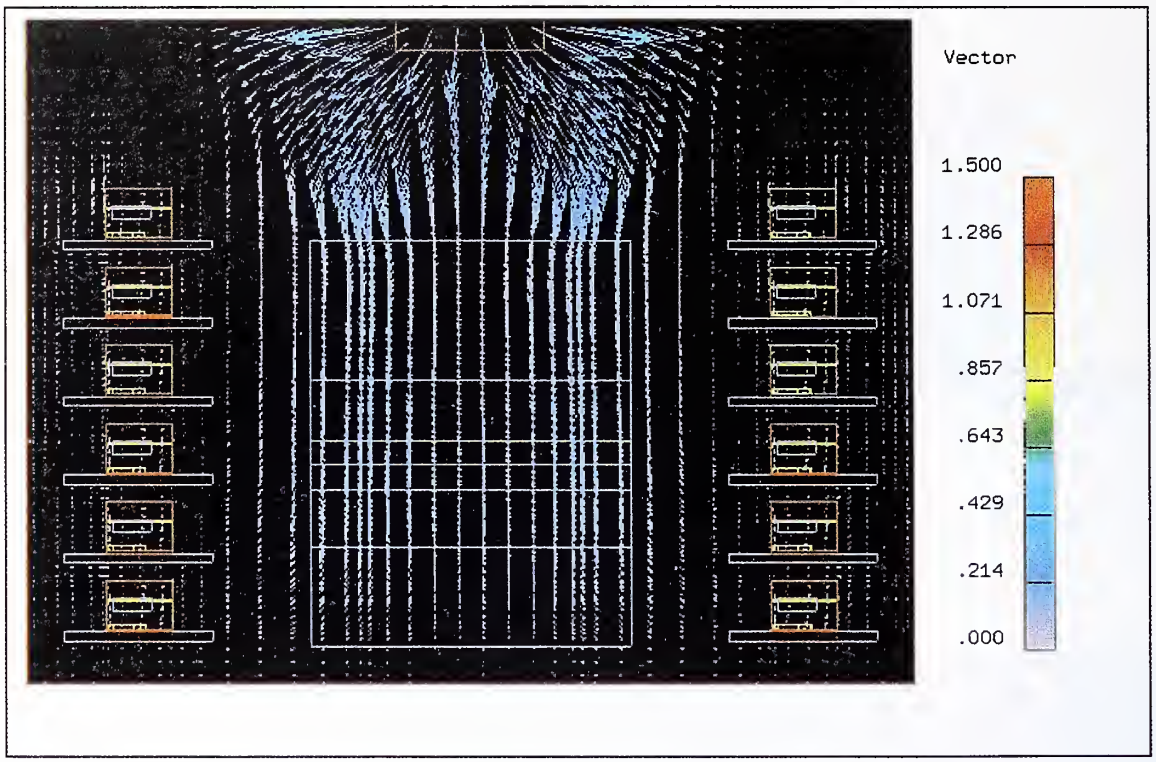

Figure 2.29 *Basecase (Case 01): Velocity Vectors (m/s)*

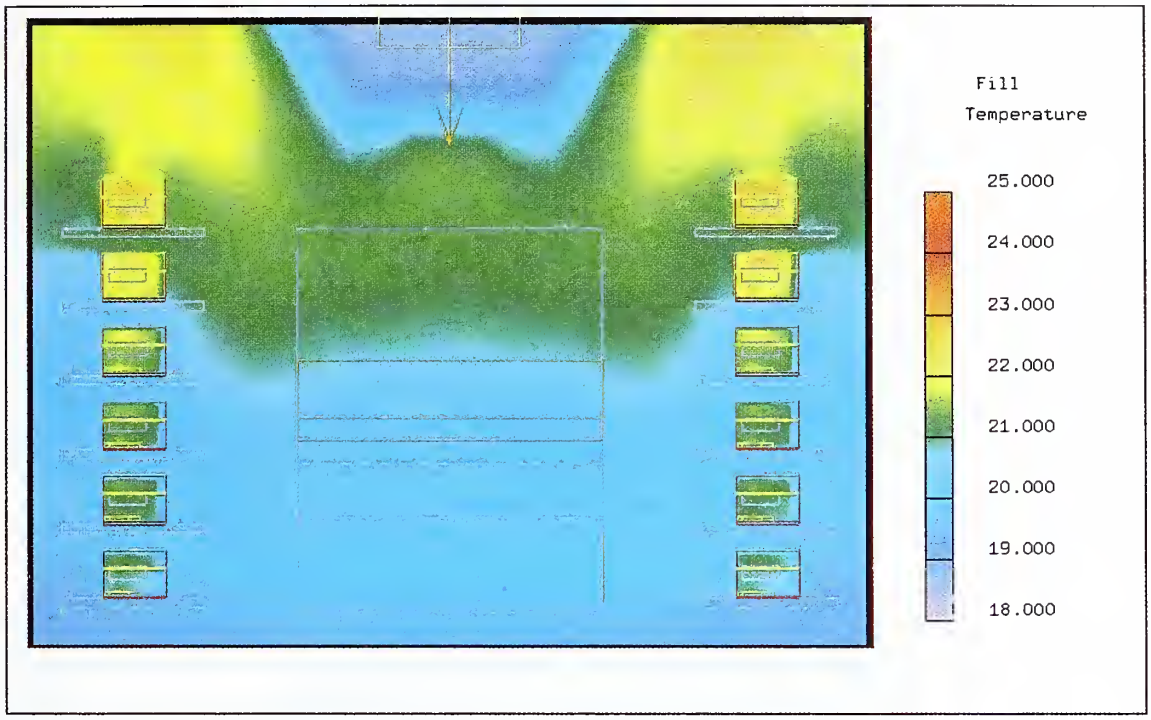

Figure 2.30 *Basecase (Case 01): Temperature Distribution (°C)*

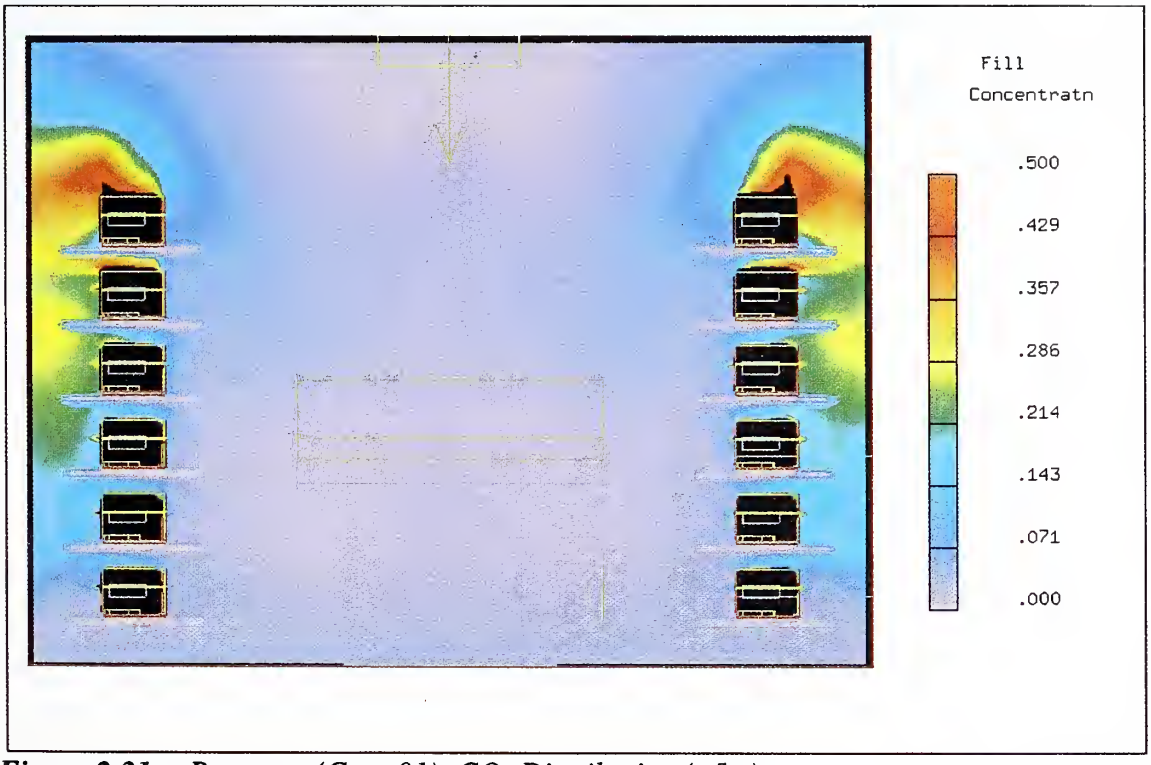

Figure 2.31 *Basecase (Case 01): CO_2 Distribution (g/kg)*

The plot of concentration of CO_2 is scaled to show the variation within the room air. The values within the cages are much higher. The concentration also rises with increasing height of the cage, which indicates that the lower cages are being ventilated better than the upper ones. This is perhaps to be expected as the flow from the supply goes down in the open center part of the room and passes through the racks towards the walls and then upwards towards the ceiling exhausts.

The CFD simulations only solved directly for the concentration of CO_2. Concentrations of NH_3 are calculated in the post processing stage of the quantitative analysis using a factor derived from the relative generation of CO_2 and NH_3. This factor varies according to the relative humidity in the cages and the number of days that have elapsed since the cage bedding was changed. So although the values shown are incorrect, the color fill for CO_2 does show the distribution of NH_3 or indeed any airborne particulate matter that flows with the air which originates from the cages. This is possible, as the concentrations of both CO_2 and NH_3 in the air are so low as to have no real effect on the density of the air, CO_2, and NH_3 mixture. In effect the CO_2 and NH_3 are intimately mixed with and flow with the air.

Figures 2.32 and 2.33 show temperature and concentration distributions in planar slices through the racks. Significantly higher temperatures and concentrations within the cages are clearly visible.

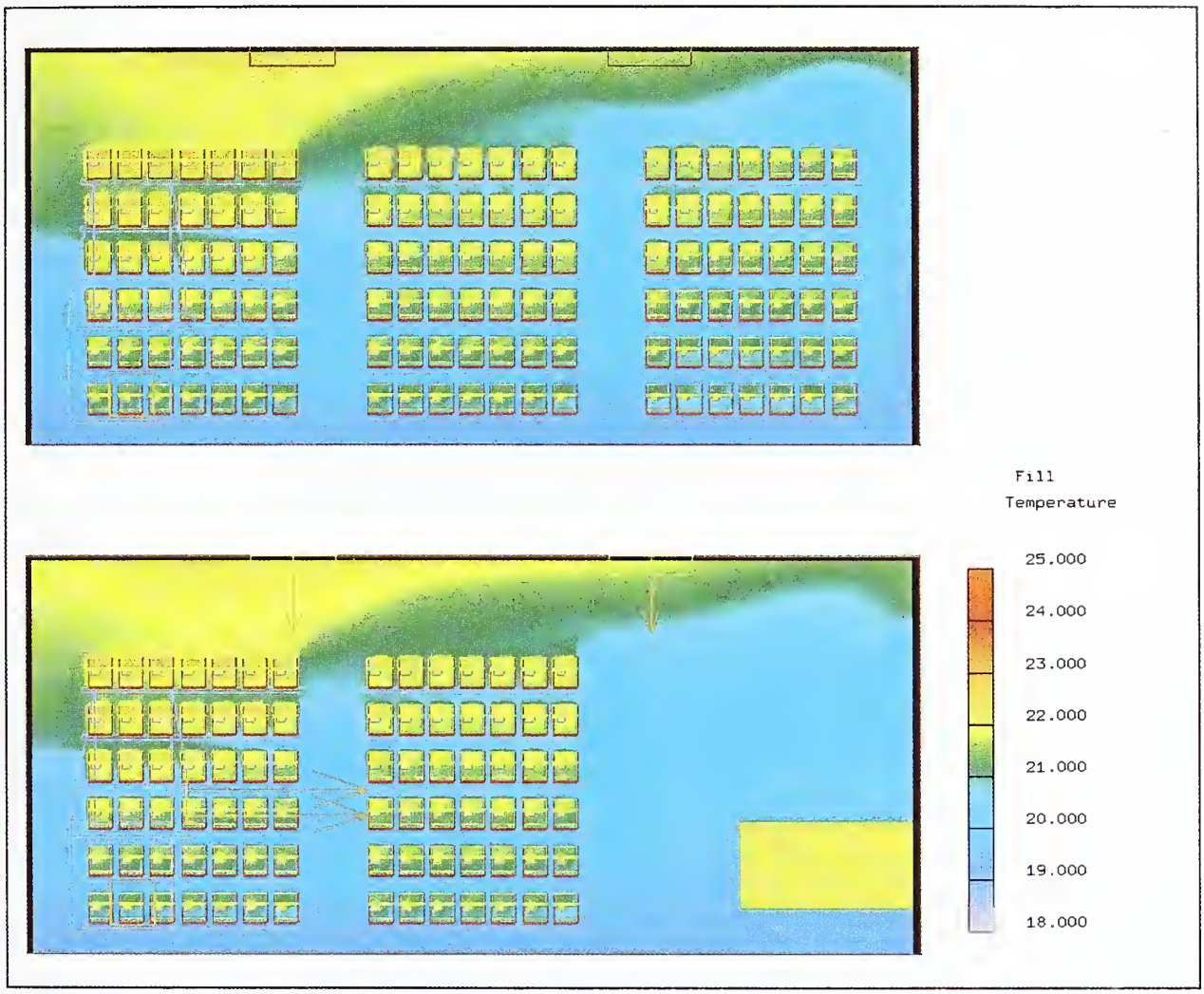

Figure 2.32 *Basecase (Case 01): Temperature Distribution (°C)*

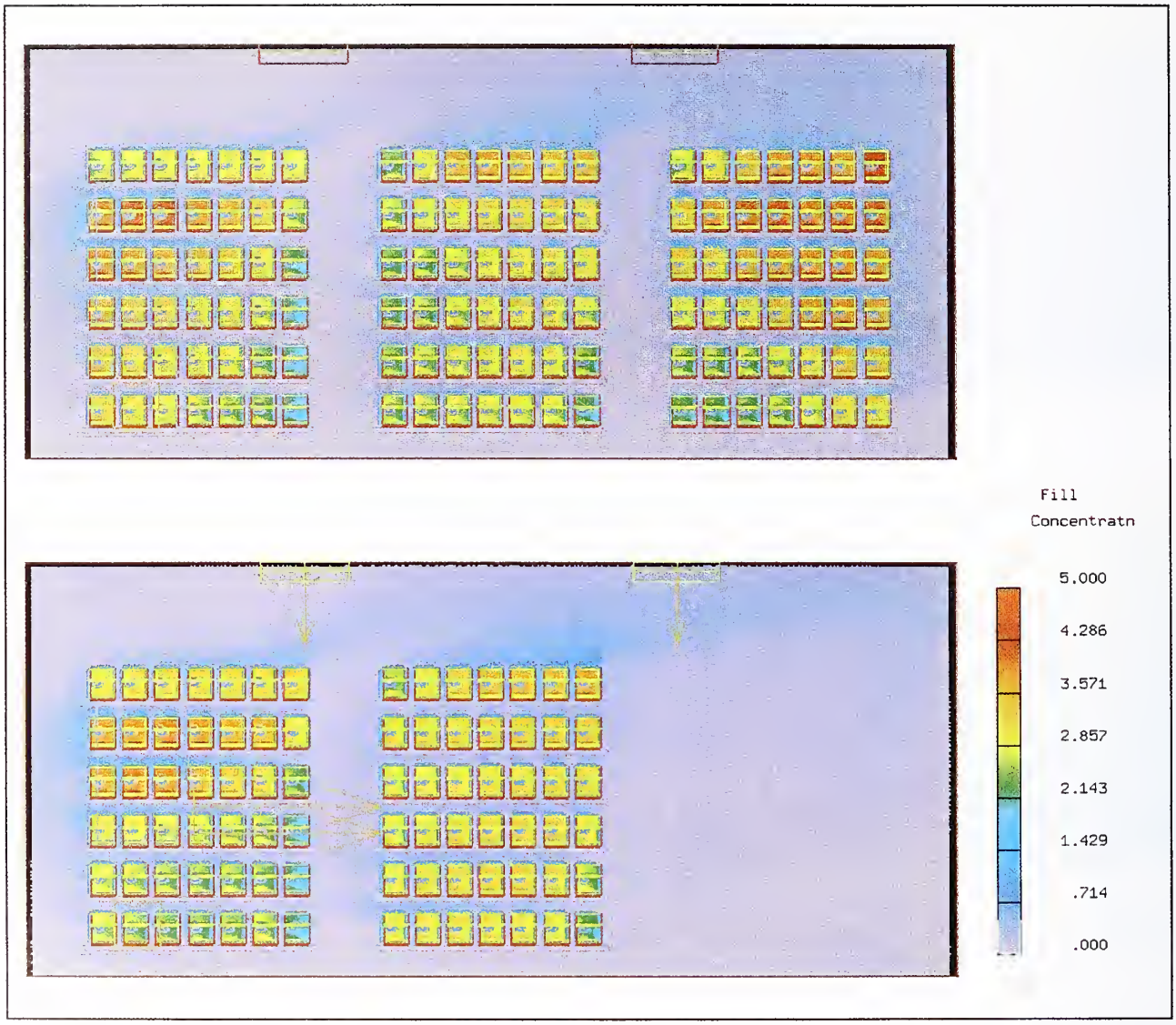

Figure 2.33 Basecase (Case 01): CO_2 Concentration (g/kg)

The temperature and CO_2 concentration for the scientist's breathing zone is shown in the table below:

Table 2.13 Basecase (Case 01): Temperature, CO_2 Concentration and RH in the Breathing Zone

	Temperature (°C (°F))	CO_2 (ppm)	RH (percent)
Mean	20.3 (68.5)	36	55.4
Maximum	21.8 (71.2)	137	-
Standard Dev.	0.5 (0.9)	20	-

The temperature is cool in the room up to the top of the breathing zone compared to the design exhaust temperature of 22.2 °C (72.0 °F). This is due to the stratification occurring in the room in combination with the location of the exhausts on the ceiling, which means that the highest temperature occurs at the exhaust at the top of the room.

The variation of NH_3 concentration in ppm in the breathing zone over the 10-day cycle is shown below:

Table 2.14 Basecase (Case 01): NH_3 Room Breathing Zone Concentrations (ppm) over a 10-Day Cycle in the Breathing Zone

	Day									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Mean	0.02	0.04	0.06	0.11	0.18	0.26	0.40	0.49	0.59	0.63
Max	0.07	0.14	0.21	0.40	0.68	1.01	1.51	1.88	2.55	2.43

This shows that the performance of the ventilation system in this room configuration is very satisfactory. The average NH_3 concentration does not rise above 0.6 ppm even after 10 days. However, the peak value rises above 1 ppm after 6 days. This indicates that any Scientist working in the area where the maximum value occurs is likely to remark that NH_3 is noticeable in the room. Too much importance should not be attached to this number because the concentration may only occur in a very small localized region in the room.

The situation in the cages is summarized below:

Table 2.15 Basecase (Case 01): Temperature CO_2 Concentration and RH in the Cages

	Temperature (°C (°F))	CO_2 (ppm)	RH (percent)
Mean	22.1 (71.8)	2158	66.8
Maximum	23.0 (73.4)	3133	66.8
Standard Dev.	0.4 (0.7)	359	2.6

Table 2.16 Basecase (Case 01): NH_3 Concentrations (ppm) over a 10-Day Cycle in the Cages

	Day									
	1	2	3	4	5	6	7	8	9	10
Mean	1.15	2.18	3.37	6.33	10.66	15.82	23.78	29.51	35.35	38.09
Max	1.67	3.17	4.89	9.19	15.47	22.96	34.53	42.84	51.32	55.30

The average NH_3 concentration in the cages rises from around 1 ppm to over 38 ppm by day 10. By day 5 the average cage NH_3 concentration is over 10 ppm. The NH_3 concentration in the worst single cage in the room (shown in the Max line in table 2.16) is approximately 50 percent higher than the average. Clearly in the latter part of the cycle the cages on average exceed the 25 ppm critical level for NH_3 by day 8 and the worst cage exceeds this value by almost 2 days earlier. That these values are not even higher is due to the good ventilation performance of the basecase room and the relatively low relative humidity values.

In a practical scenario where the bedding is changed after four days the room would not be considered smelly, although the individual cages would be.

The summary sheets for each run also contain three histograms that show the variation of RH concentration and temperature in the cages. The histograms show the number of cages (frequency) that have values which fall in the range between two values marked on the horizontal axis, with only the upper value indicated. For example, in figure 2.34 the column labeled 67 indicates that 35 cages have an RH between 66 percent and 67 percent. The concentration histogram can be converted to CO_2 and NH_3 concentrations by multiplying the kg/kg values given in the chart by a conversion factor. The conversion factors are given for the basecase in table 2.17 below:

Table 2.17 Conversion Factor between kg/kg and ppm for CO_2 and NH_3 Concentrations

Day	CO_2	NH_3
1	785000	418
2	785000	795
3	785000	1225
4	785000	1922
5	785000	2848
6	785000	3443
7	785000	8409
8	785000	8483
9	785000	8442
10	785000	11384

The plots for the basecase are shown below. These show virtually a standard Gaussian bell-shaped distribution around the mean values. Comparison of these histograms for the different

room configurations identify rooms that provide uniform conditions in all cages or those that have excessive variation in cage conditions that could influence the experimental investigation being undertaken in the room.

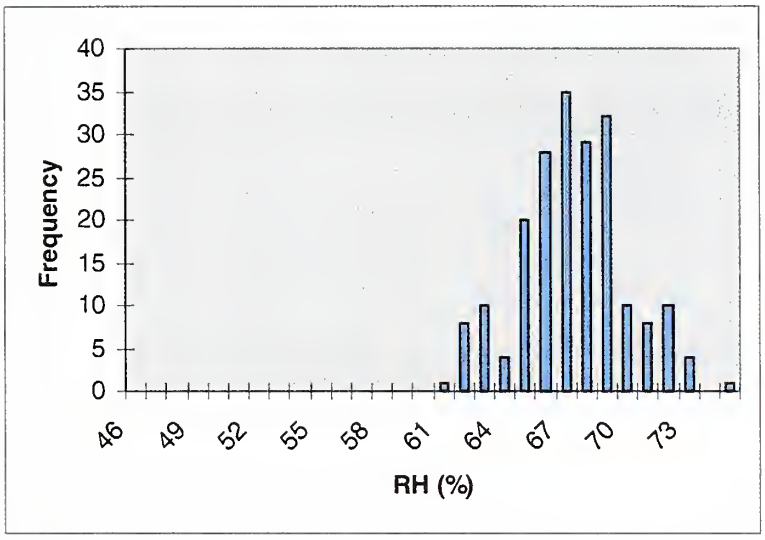

Figure 2.34 *Basecase (Case 01): Cage Relative Humidity (percent)*

The distribution of relative humidity shows the average for all the cages around 67 percent, with a significant number around 73 percent and above, which is around 20 percent above the average room relative humidity.

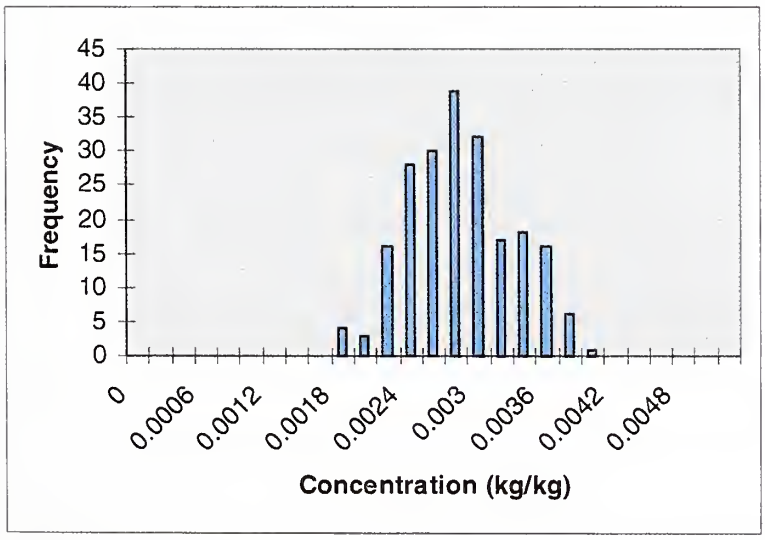

Figure 2.35 *Basecase (Case 01): Cage CO_2 Concentration (kg/kg)*

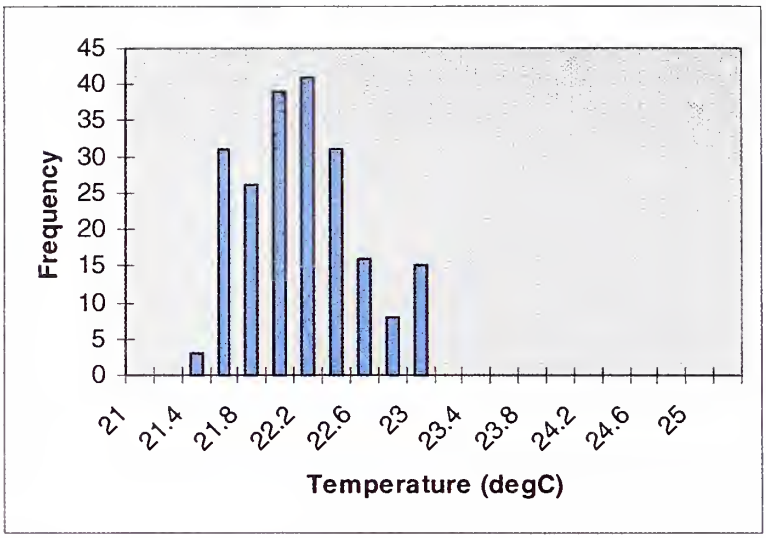

Figure 2.36 *Basecase (Case 01): Cage Temperatures (°C)*

SECTION III

EVALUATION OF RESULTS AND RECOMMENDATIONS

SECTION III: TABLE OF CONTENTS

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3. EVALUATION OF RESULTS AND RECOMMENDATIONS

This section presents and discusses the results generated in the CFD simulations for 101 different room configurations. The detailed flow patterns for each room are not discussed; the comparisons focus on the quantitative analysis of the CFD data.

The analysis concentrates on eight parameters defined in section 2.4.2:

- Mean cage temperatures
- Mean cage CO_2 concentrations
- Mean cage relative humidity (RH)
- Mean cage NH_3 concentration on day 4
- Mean room breathing zone temperature
- Mean room breathing zone CO_2 concentration
- Mean room breathing zone (RH)
- Mean room breathing zone NH_3 concentration on day 4

As each day had a different NH_3 generation rate, the NH_3 concentrations are different on each day. However as the underlying mass fraction information and RH information does not change on a daily basis in the simulations, room performance can be compared by using the results for any of the 10 days. For ease of comparison, results are presented for day 4, which corresponds to the day most widely used to change the bedding in the mice cages.

In addition to the day 4 NH_3 concentrations (i.e., the conditions that would arise four days after clean bedding is placed in every cage), a summary of the complete 10-day cycle is presented.

The analysis focuses on trends in the data that identify any ventilation schemes as particularly good or bad, and recommendations are made. The major recommendation is tested by further post-processing of the CFD data.

3.1 Results for 101 Room Simulations

Figures 3.01 to 3.08 show bar charts of the eight parameters identified as important in categorizing the behavior of the ventilation system on the room and the cages. The individual cases can be identified by comparison of the case number on the bottom of the charts with the complete list of cases in table 3.01 below.

Table 3.01 List of All Whole Room Runs

Case Name	Supply Diffuser Type	Exhaust Location and Number	Change Station (Design/ Status)	Rack Orientation	Rack Density	Pressure of Room to Corridor	Supply Temperature °C (°F)	Supply ACH
Basecase	Radial	Ceiling (x2)	Thoren/ ON	Parallel	Single	Neg.. 100cfm	18.8 (65.8)	15
Case 02	Radial	High (x4)	Thoren/ ON	Parallel	Single	Neg.. 100cfm	18.8 (65.8)	15
Case 03	Radial	Low (x4)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 04	Slot	Ceiling (x2)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 05	Slot	High (x4)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 06	Slot	Low (x4)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 07	Low Ind	Ceiling (x2)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 08	Low Ind	High (x4)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 09	Low Ind	Low (x4)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 10	Radial	Ceiling (x2)	Thoren/ OFF	Parallel	Single	Neg. 100cfm	20.7 (69.3)	15
Case 11	Radial	Low (x4)	Thoren/ OFF	Parallel	Single	Neg. 100cfm	20.7 (69.3)	15
Case 12	Slot	Ceiling (x2)	Thoren/ OFF	Parallel	Single	Neg. 100cfm	20.7 (69.3)	15
Case 13	Slot	Low (x4)	Thoren/ OFF	Parallel	Single	Neg. 100cfm	20.7 (69.3)	15
Case 14	Low Ind	Ceiling (x2)	Thoren/ OFF	Parallel	Single	Neg. 100cfm	20.7 (69.3)	15
Case 15	Low Ind	Low (x4)	Thoren/ OFF	Parallel	Single	Neg. 100cfm	20.7 (69.3)	15
Case 16	Radial	Ceiling (x2)	Thoren/ ON	Parallel	Single	Pos. 100cfm	18.8 (65.8)	15
Case 17	Slot	Ceiling (x2)	Thoren/ ON	Parallel	Single	Pos. 100cfm	18.8 (65.8)	15
Case 18	Low Ind	Ceiling (x2)	Thoren/ ON	Parallel	Single	Pos. 100cfm	18.8 (65.8)	15
Case 19	Radial	Ceiling (x2)	Thoren/ ON	Perpendicular	Single	Neg. 100cfm	18.8 (65.8)	15
Case 20	Slot	Ceiling (x2)	Thoren/ ON	Perpendicular	Single	Neg. 100cfm	18.8 (65.8)	15
Case 21	Low Ind	Ceiling (x2)	Thoren/ ON	Perpendicular	Single	Neg. 100cfm	18.8 (65.8)	15
Case 22	Radial	Low (x4)	Thoren/ ON	Perpendicular	Single	Neg. 100cfm	18.8 (65.8)	15
Case 23	Slot	Low (x4)	Thoren/ ON	Perpendicular	Single	Neg. 100cfm	18.8 (65.8)	15
Case 24	Low Ind	Low (x4)	Thoren/ ON	Perpendicular	Single	Neg. 100cfm	18.8 (65.8)	15
Case 25 *	Radial	Ceiling (x2)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 26 *	Slot	Ceiling (x2)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 27 *	Low Ind	Ceiling (x2)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 28	Low Ind	Low (x4)	Thoren/ ON	Parallel	Single	Neg. 100cfm	16.8 (62.2)	10
Case 29	Low Ind	Low (x4)	Thoren/ ON	Parallel	Single	Neg. 100cfm	11.0 (51.8)	5
Case 30	Low Ind	Low (x4)	Thoren/ ON	Parallel	Single	Neg. 100cfm	19.8 (67.6)	20
Case 31	Radial	Low (x4)	Thoren/ ON	Perpendicular	Double	Neg. 100cfm	17.5 (63.5)	15
Case 32	Slot	Low (x4)	Thoren/ ON	Perpendicular	Double	Neg. 100cfm	17.5 (63.5)	15
Case 33	Low Ind	Low (x4)	Thoren/ ON	Perpendicular	Double	Neg. 100cfm	17.5 (63.5)	15
Case 34	Radial	Ceiling (x2)	Thoren/ ON	Perpendicular	Double	Neg. 100cfm	17.5 (63.5)	15
Case 35	Slot	Ceiling (x2)	Thoren/ ON	Perpendicular	Double	Neg. 100cfm	17.5 (63.5)	15
Case 36	Low Ind	Ceiling (x2)	Thoren/ ON	Perpendicular	Double	Neg. 100cfm	17.5 (63.5)	15
Case 37	Radial	Ceiling (x1) / Low (x4) (Mass flow in 50/50 split)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 38	Slot	Ceiling (x1) / Low (x4) (Mass flow in 50/50 split)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 39	Low Ind	Ceiling (x1) / Low (x4) (Mass flow in 50/50 split)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 40	Radial	Ceiling (x4)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15

Case Name	Supply Diffuser Type	Exhaust Location and Number	Change Station (Design/ Status)	Rack Orientation	Rack Density	Pressure of Room to Corridor	Supply Temperature °C (°F)	Supply ACH
Case 41	Slot	Ceiling (x4)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 42	Low Ind	Ceiling (x4)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 43	Low Ind (rotated by 90°)	Ceiling (x2)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 44	Radial (rotated by 90°)	Ceiling (x2)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 45	Radial	Ceiling (x2)	Thoren/ ON	Parallel	Single	Neg. 50cfm	18.8 (65.8)	15
Case 46	Radial	Ceiling (x2)	Thoren/ ON	Parallel	Single	Neutral	18.8 (65.8)	15
Case 47	Radial	Ceiling (x2)	Thoren/ ON	Parallel	Single	Pos. 50cfm	18.8 (65.8)	15
Case 48	Radial	Ceiling (x2)	Thoren/ ON (swapped with rack1)	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 49	Radial	Ceiling (x2)	Thoren/ ON (swapped with rack2)	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 50	Radial	Ceiling (x2)	Thoren/ ON (swapped with rack3)	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 51	Radial	Ceiling (x2)	Thoren/ ON (swapped with rack4)	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 52	Radial	Ceiling (x2)	Thoren/ ON (swapped with rack5)	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 53	Radial	Ceiling (x2)	Lab. Prod. / ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 54	Slot	Ceiling (x2)	Lab. Prod. / ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 55	Low Ind	Ceiling (x2)	Lab. Prod. / ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 56	Radial	High (x4)	Lab. Prod. / ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 57	Radial	Low (x4)	Lab. Prod. / ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 58	Slot	High (x4)	Lab. Prod. / ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 59	Slot	Low (x4)	Lab. Prod. / ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 60	Low Ind	High (x4)	Lab. Prod. / ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 61	Low Ind	Low (x4)	Lab. Prod. / ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 62	Low Ind	Low (x4)	Thoren/ ON	Perpendicular	Double	Neg. 100cfm	6.6 (43.9)	5
Case 63	Low Ind	Low (x4)	Thoren/ ON	Perpendicular	Double	Neg. 100cfm	14.8 (58.6)	10
Case 64	Low Ind	Low (x4)	Thoren/ ON	Perpendicular	Double	Neg. 100cfm	18.9 (66.0)	20
Case 65	Low Ind	Low (x4)	Lab. Prod. / ON	Perpendicular	Double	Neg. 100cfm	17.5 (63.5)	15
Case 66	Low Ind	Low (x4)	Lab. Prod. / ON	Perpendicular	Double	Neg. 100cfm	6.6 (43.9)	5
Case 67	Low Ind	Low (x4)	Lab. Prod. / ON	Perpendicular	Double	Neg. 100cfm	14.8 (58.6)	10
Case 68	Low Ind	Low (x4)	Lab. Prod. / ON	Perpendicular	Double	Neg. 100cfm	18.9 (66.0)	20

Case Name	Supply Diffuser Type	Exhaust Location and Number	Change Station (Design/ Status)	Rack Orientation	Rack Density	Pressure of Room to Corridor	Supply Temperature °C (°F)	Supply ACH
Case 69	Radial	High (x4) / Low (x4) (Mass flow split evenly amongst exhausts)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 70	Slot	High (x4) / Low (x4) (Mass flow split evenly amongst exhausts)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 71	Low Ind	High (x4) / Low (x4) (Mass flow split evenly amongst exhausts)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 72	Radial	High (x4) / Low (x2) (Mass flow split evenly amongst exhausts)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 73	Slot	High (x4) / Low (x2) (Mass flow split evenly amongst exhausts)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 74	Low Ind	High (x4) / Low (x2) (Mass flow split evenly amongst exhausts)	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 75	Radial	Ceiling (x1) / Low (x4) (Mass flow in 50/50 split)	Lab. Prod. / ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 76 **	Radial	Ceiling (x2)	Thoren/ ON	Parallel	Single	Neg. 100cfm	19.2 (66.6)	15
Case 77 **	Slot	Ceiling (x2)	Thoren/ ON	Parallel	Single	Neg. 100cfm	19.2 (66.6)	15
Case 78 **	Low Ind	Ceiling (x2)	Thoren/ ON	Parallel	Single	Neg. 100cfm	19.2 (66.6)	15
Case 79	Radial	2 Door exhausts	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 80	Slot	2 Door exhausts	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 81	Low Ind	2 Door exhausts	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 82	Radial	2 Door exhausts	Thoren/ ON	Parallel	Single	Neg. 100cfm	18.8 (65.8)	15
Case 83	Slot	2 Door exhausts	Thoren/ ON	Perpendicular	Double	Neg. 100cfm	17.5 (63.5)	15
Case 84	Low Ind	2 Door exhausts	Thoren/ ON	Perpendicular	Double	Neg. 100cfm	17.5 (63.5)	15
Case 85	Radial	Low (x4)	Lab. Prod. / ON	Perpendicular	Double	Neg. 100cfm	17.5 (63.5)	15
Case 86	Slot	Low (x4)	Lab. Prod. / ON	Perpendicular	Double	Neg. 100cfm	17.5 (63.5)	15
Case 87	Radial	Low (x4)	Thoren/ ON	Parallel	Reduced	Neg. 100cfm	19.2 (66.6)	15

Case Name	Supply Diffuser Type	Exhaust Location and Number	Change Station (Design/ Status)	Rack Orientation	Rack Density	Pressure of Room to Corridor	Supply Temperature °C (°F)	Supply ACH
Case 88	Slot	Low (x4)	Thoren/ ON	Parallel	Reduced	Neg. 100cfm	19.2 (66.6)	15
Case 89	Low Ind	Low (x4)	Thoren/ ON	Parallel	Reduced	Neg. 100cfm	19.2 (66.6)	15
Case 90	Radial	Ceiling (x2)	Thoren/ ON	Perpendicular all 5 on 1 wall	Single	Neg. 100cfm	18.8 (65.8)	15
Case 91	Slot	Ceiling (x2)	Thoren/ ON	Perpendicular all 5 on 1 wall	Single	Neg. 100cfm	18.8 (65.8)	15
Case 92	Low Ind	Ceiling (x2)	Thoren/ ON	Perpendicular all 5 on 1 wall	Single	Neg. 100cfm	18.8 (65.8)	15
Case 93	Radial	Ceiling (x2)	Thoren/ ON	Perpendicular all 5 on 1 wall	Double	Neg. 100cfm	17.5 (63.5)	15
Case 94	Slot	Ceiling (x2)	Thoren/ ON	Perpendicular all 5 on 1 wall	Double	Neg. 100cfm	17.5 (63.5)	15
Case 95	Low Ind	Ceiling (x2)	Thoren/ ON	Perpendicular all 5 on 1 wall	Double	Neg. 100cfm	17.5 (63.5)	15
Case 96	Radial	Ceiling (x2)	Lab. Prod. / ON	Perpendicular all 5 on 1 wall	Double	Neg. 100cfm	17.5 (63.5)	15
Case 97	Slot	Ceiling (x2)	Lab. Prod. / ON	Perpendicular all 5 on 1 wall	Double	Neg. 100cfm	17.5 (63.5)	15
Case 98	Low Ind	Ceiling (x2)	Lab. Prod. / ON	Perpendicular all 5 on 1 wall	Double	Neg. 100cfm	17.5 (63.5)	15
Case 99 ***	Radial	Ceiling (x2)	Thoren/ ON	Parallel	Single	Neg. 100cfm	22.2 (72.0)	15
Case 100 ***	Radial	Low (x4)	Thoren/ ON	Parallel	Single	Neg. 100cfm	22.2 (72.0)	15
Case 101 ***	Low Ind	Low (x4)	Lab. Prod. / ON	Perpendicular	Double	Neg. 100cfm	22.2 (72.0)	5

* Sealed cages instead of open cages

** Room 4.26m (14') wide instead of 3.66m (12')

*** Supply air temperature fixed at 22.2 °C (72.0 °F). In all other cases, the exhaust temperature was set to be 22.2 °C (72.0 °F) by setting the supply air temperature appropriately.

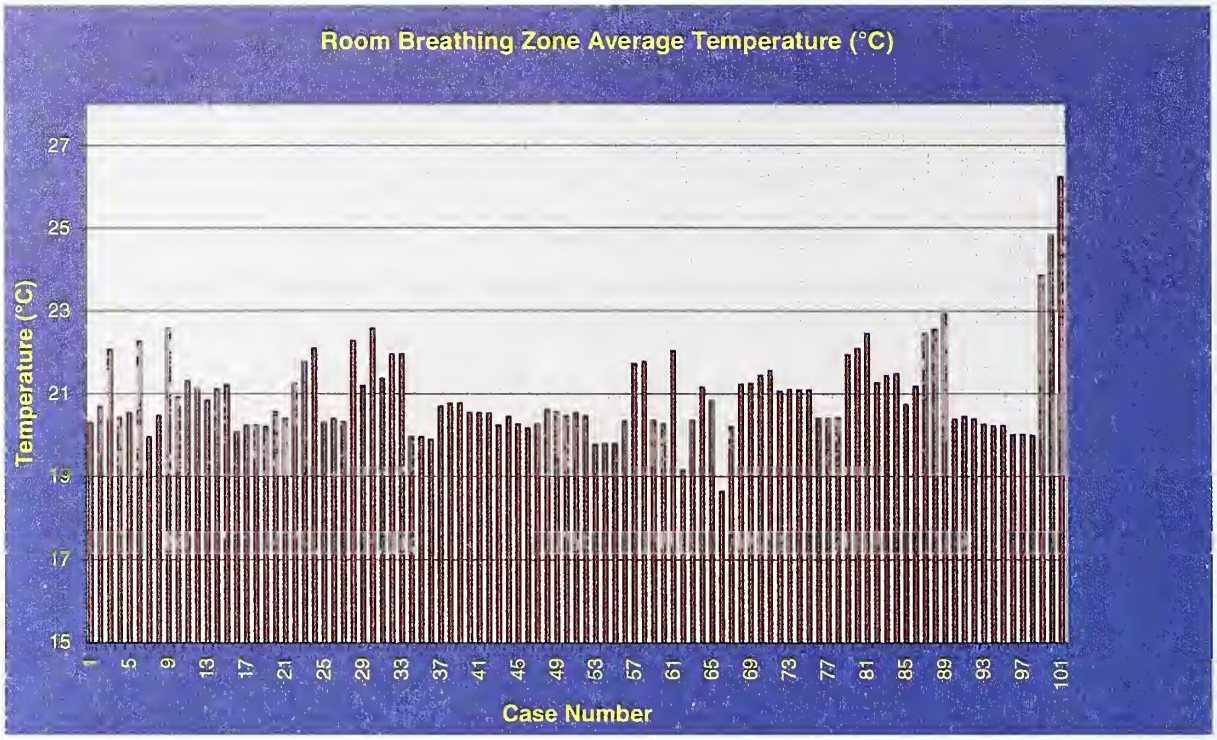


Figure 3.01 *Mean Room Breathing Zone Temperature*

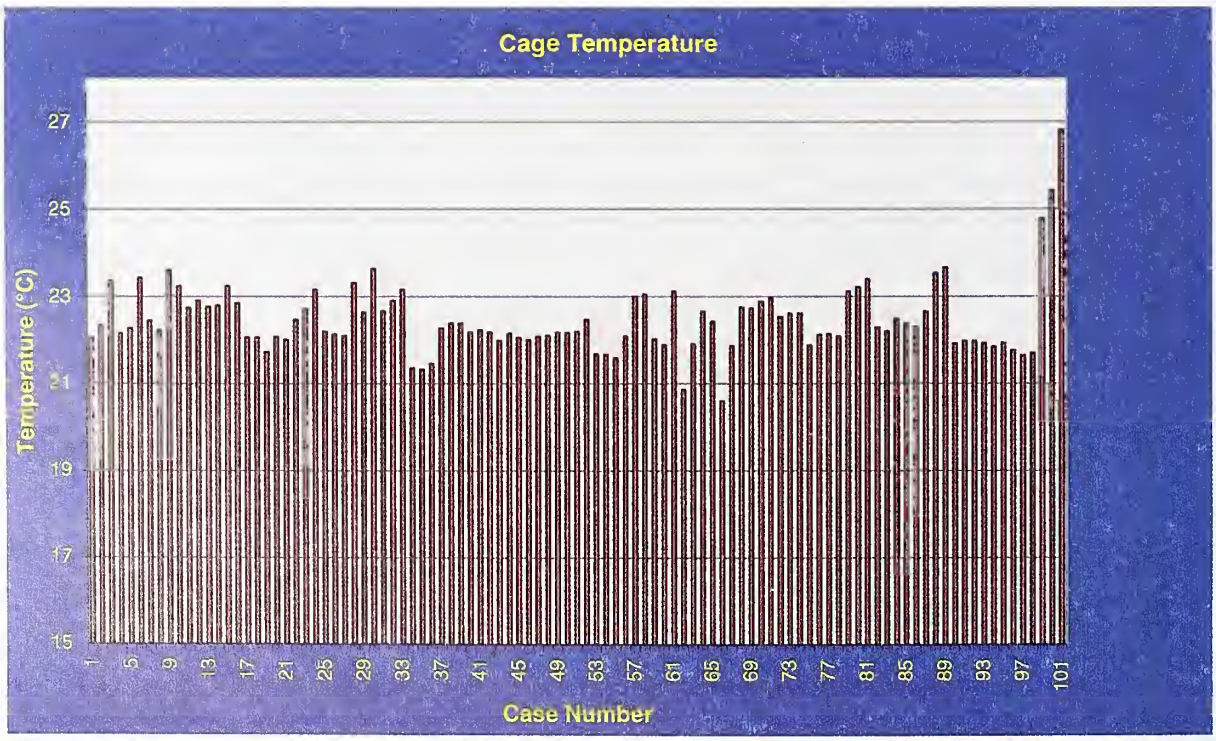


Figure 3.02 *Mean Cage Temperatures*

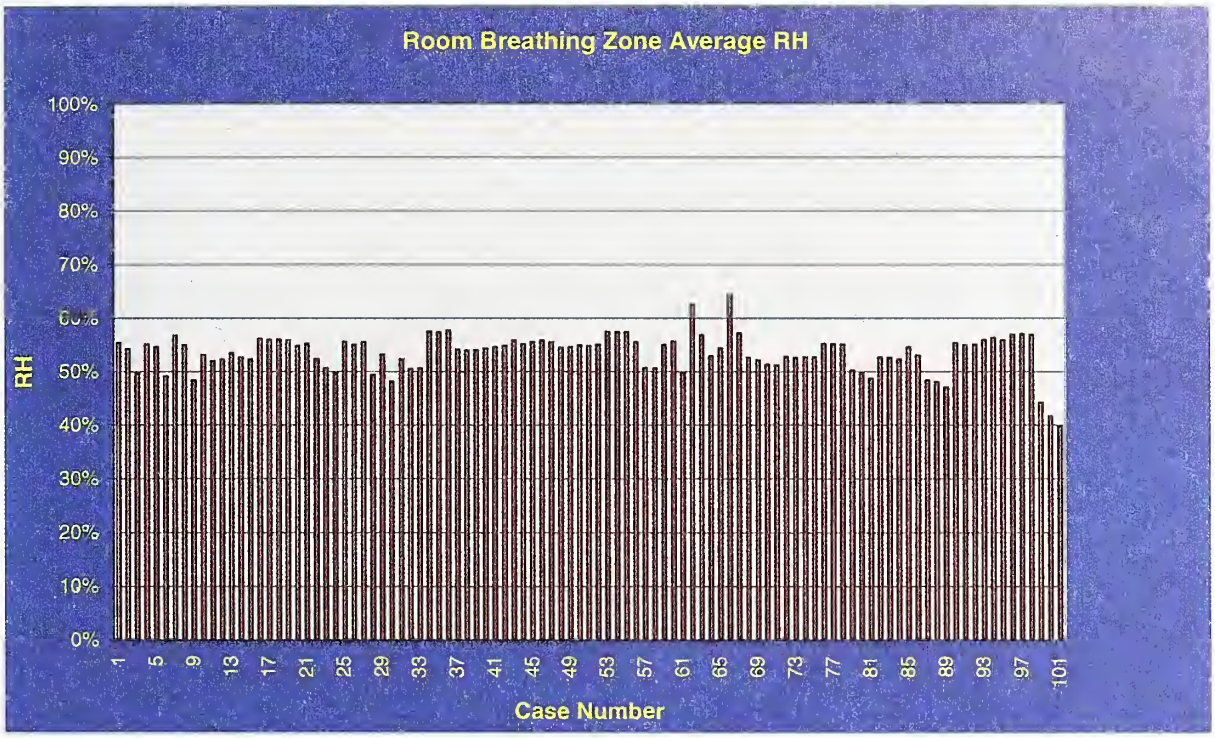


Figure 3.03 *Mean Room Breathing Zone Relative Humidity (RH)*

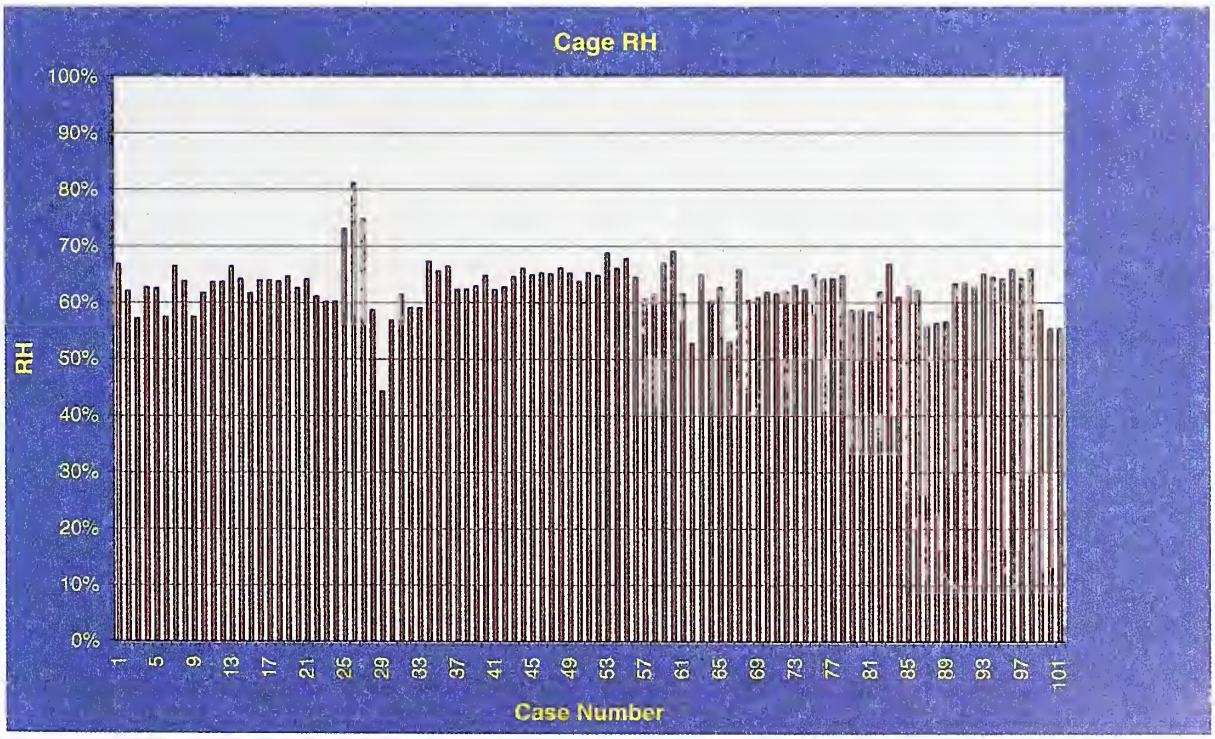


Figure 3.04 *Mean Cage Relative Humidity (RH)*

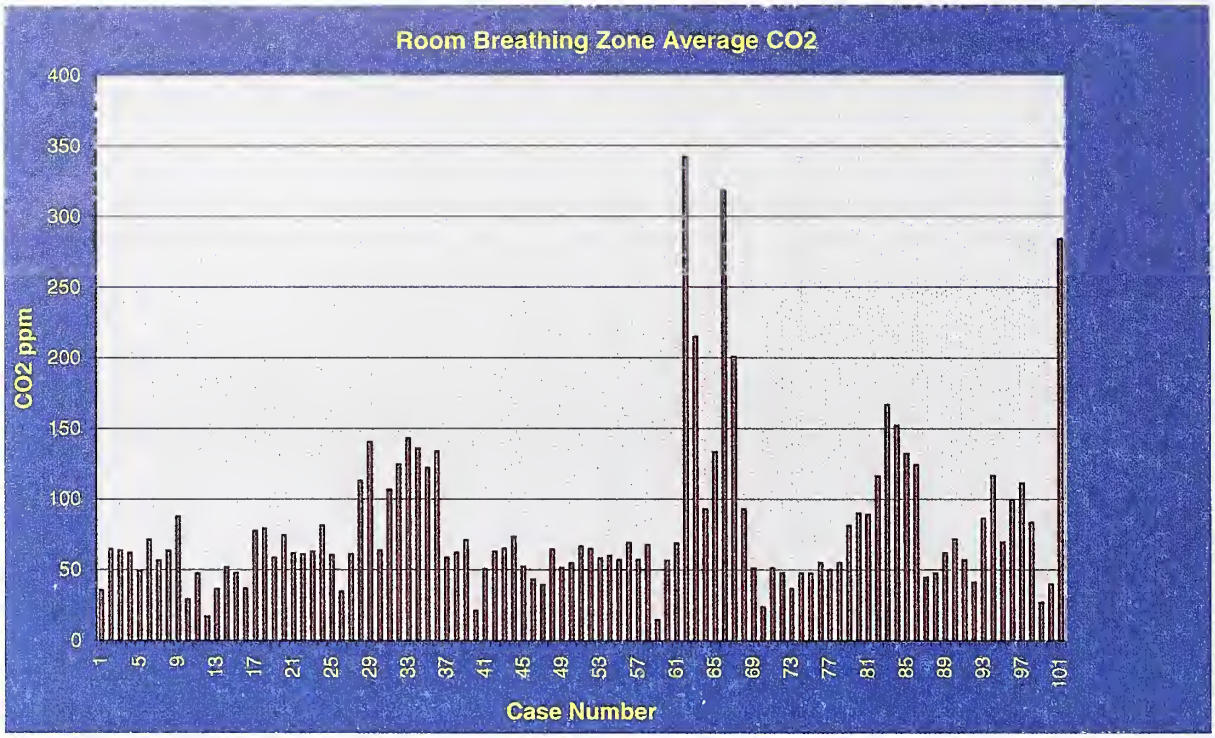


Figure 3.05 *Mean Room Breathing Zone CO_2 Concentration*

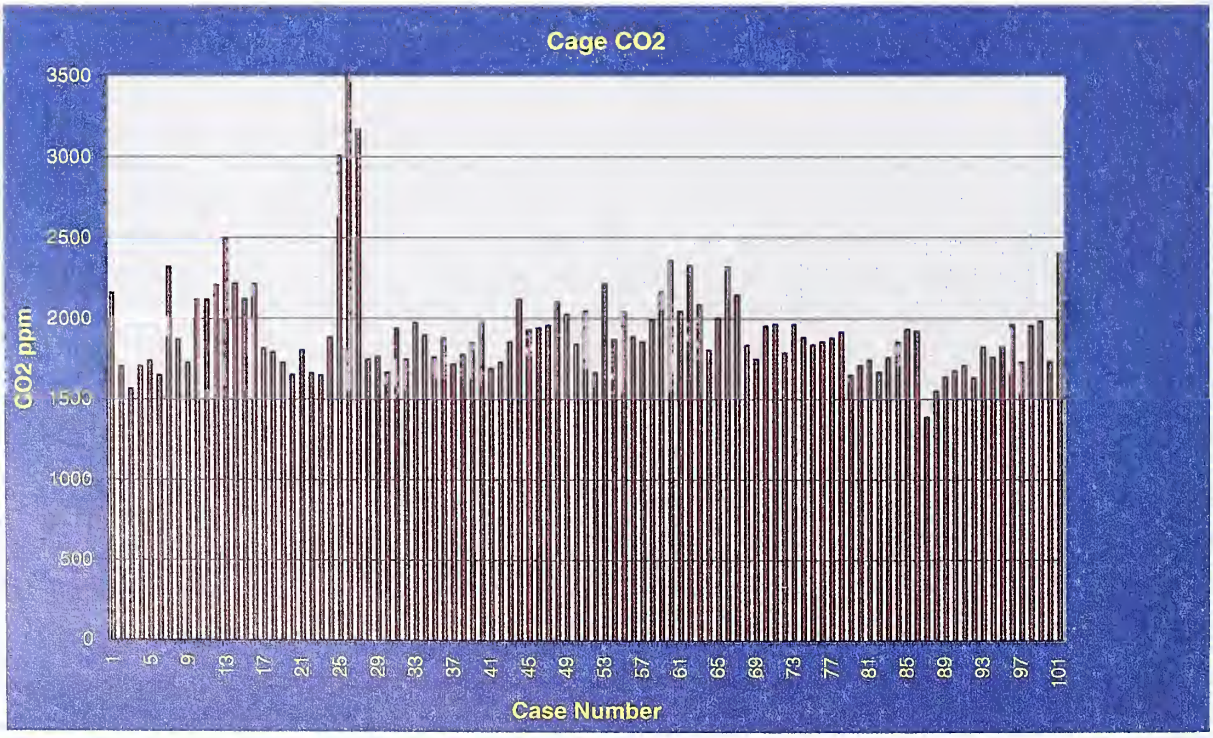


Figure 3.06 *Mean Cage CO_2 Concentration*

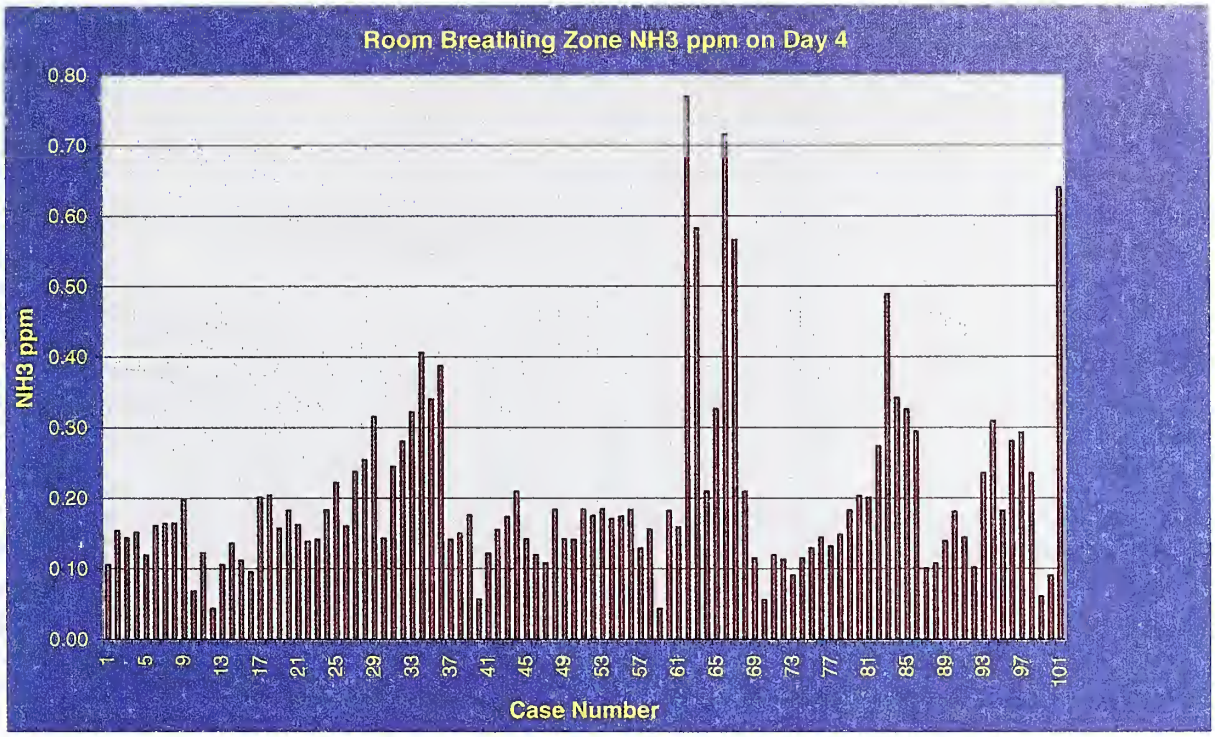


Figure 3.07 *Mean Room Breathing Zone NH_3 Concentration on Day 4*

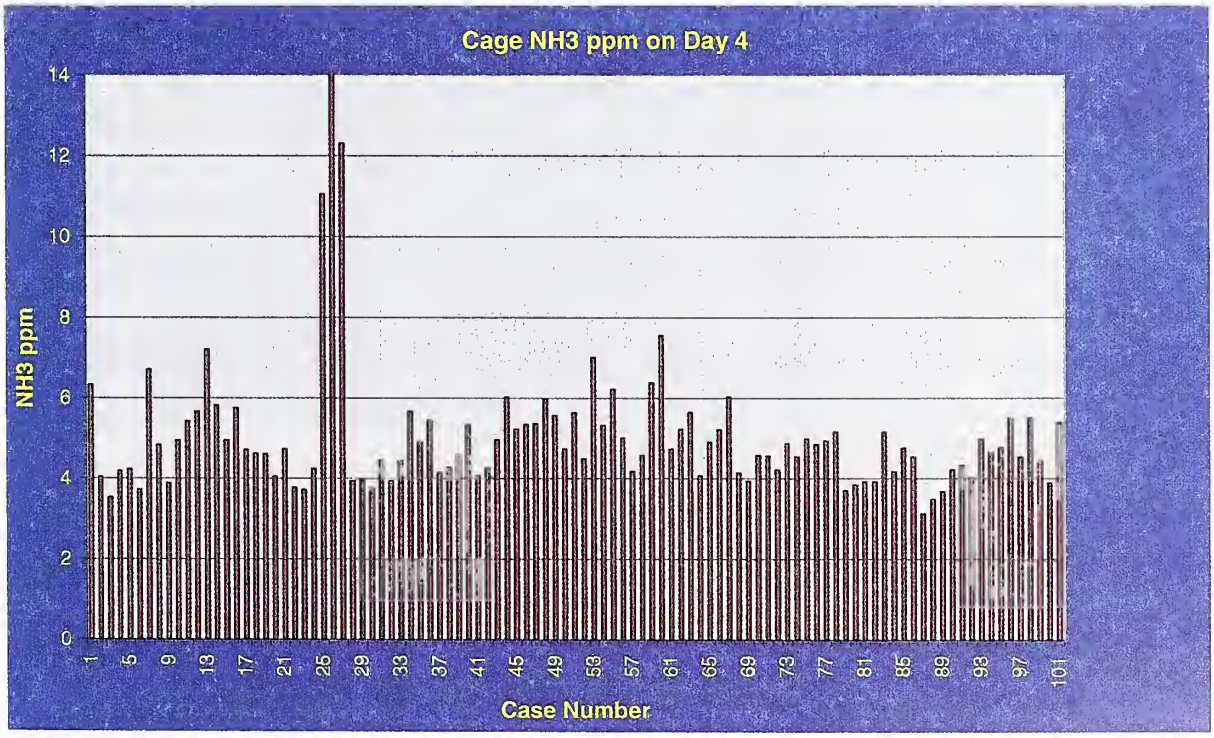


Figure 3.08 *Mean Cage NH_3 Concentration on Day 4*

Before the detailed comparison of the room configurations, which follows this section, a few general remarks on the results are appropriate.

The ventilation in the rooms was designed to produce 22.2 °C (72.0 °F) at the exhausts in the room (except for cases 99-101). This leads to the room and cage temperatures that do not vary greatly. The variation that does occur seems to be mostly due to temperature stratification in the rooms (i.e., the temperature rises towards the ceiling) in combination with the exhaust position. A low level exhaust means that the design temperature of 22.2 °C (72.0 °F) is the "lowest" in the room whereas a high level exhaust means the temperature should be below 22.2 °C (72.0 °F) in the room.

The CO_2 concentrations are a simple indicator of the ventilation in the room and cages. High values indicate poor ventilation. Good ventilation of the cages can lead to higher values in the room space.

The NH_3 concentration data are more complex measures of the ventilation as they also depend on the relative humidity in the cages, which is also dependent on the temperature. Therefore, poor ventilation of cages at a high temperature and low humidity may produce low NH_3 concentrations.

In making comparisons among the values shown for the cages on the charts, it is important to consider if the differences in the mean values (the average for all cages) is statistically significant. The ANOVA test (see section 6) can be used to determine significant differences. This test was run for several pairs of datasets. In each case the differences were found to be significant, except when the means were actually identical. Please note that comparing 101 datasets with each other for 4 data values produces more than 40,000 tests. This seems to be a result of having 210 or 420 cages in the rooms. Each one appears as a sampling point for the test. With so many samples the test becomes very sensitive and even small variations in means are statistically significant.

3.1.1 Supply Type and Exhaust Position

Cases 1 to 9 allow an easy comparison of the effect of Supply type and exhaust position. Cases 1 (the basecase) to 3 had a radial diffuser supply with ceiling, high level (on side walls) and low level (on side walls) exhausts, respectively. Cases 4 to 6 used a slot diffuser, and cases 7 to 9 a low induction diffuser with the same exhaust configurations.

Figures 3.09 to 3.16 show three-dimensional bar charts comparing temperature, CO_2, NH_3, and relative humidity for both the cages and scientists' breathing zone in the center of the room.

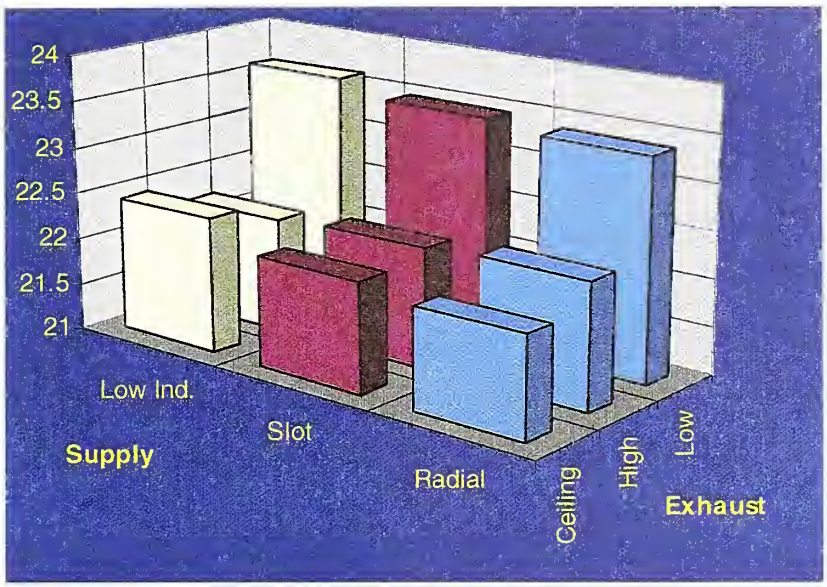


Figure 3.09 *Comparison of Mean Cage Temperatures (°C)*

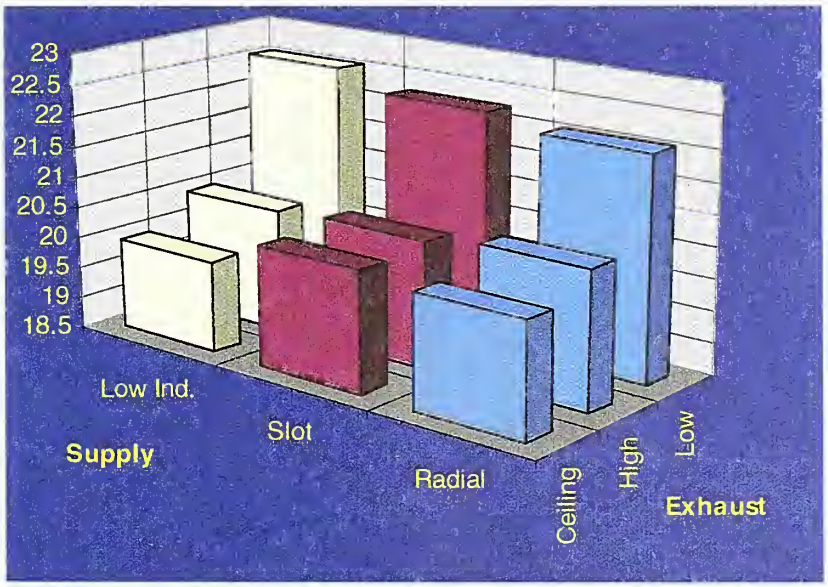


Figure 3.10 *Comparison of Room Breathing Zone Temperatures (°C)*

The higher temperatures, about 2 °C (4 °F) produced in both the cages and breathing zone in the low level exhaust runs indicates this exhaust location is less efficient in cooling the room compared with the high and ceiling level.

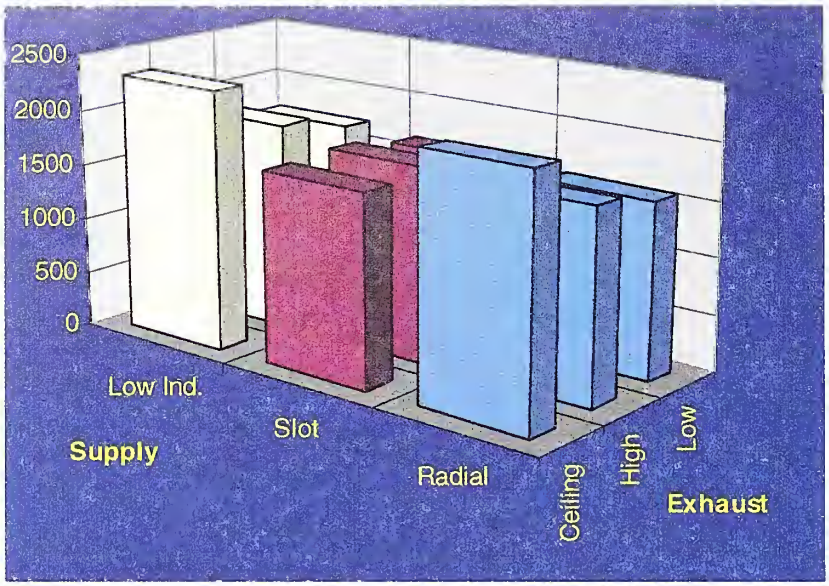


Figure 3.11 Comparison of Mean Cage CO_2 Concentration (ppm)

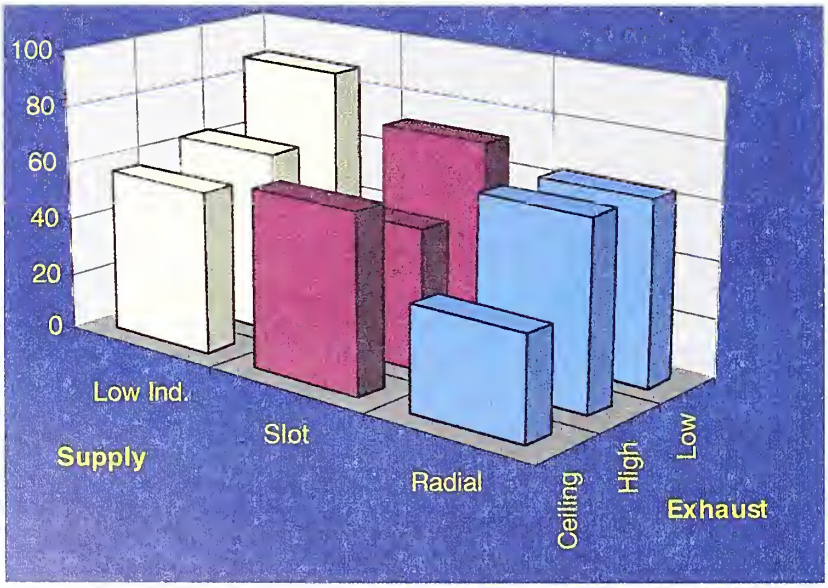


Figure 3.12 Comparison of Room Breathing Zone CO_2 Concentration (ppm)

The lower values of CO_2 concentration in the cages for the low level exhaust (up to 27 percent for the radial diffuser, 4 percent for the slot diffuser and 25 percent for the low induction diffuser) indicate that the cages are better ventilated in this situation. The room values show the best ventilation occurs with a radial diffuser and ceiling level exhausts.

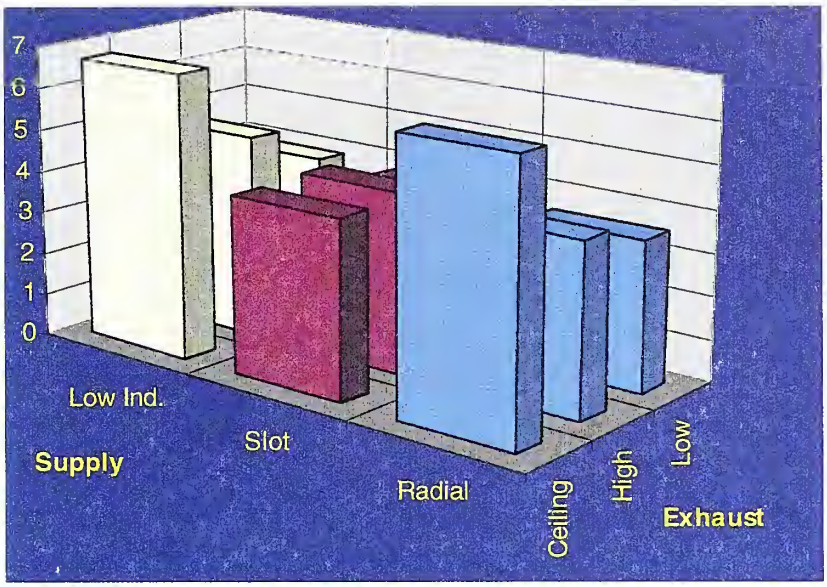


Figure 3.13 *Comparison of Mean Cage NH_3 Concentration (ppm)*

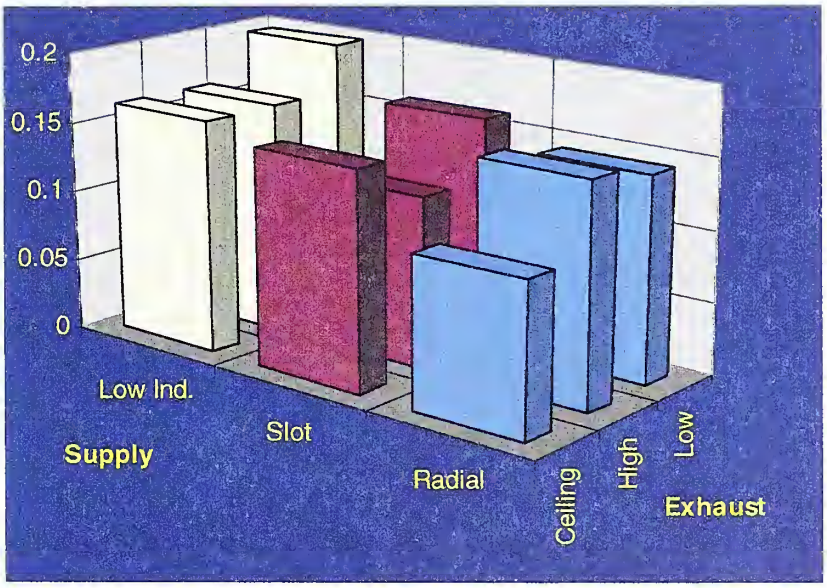


Figure 3.14 *Comparison of Room Breathing Zone NH_3 Concentration (ppm)*

The cage NH_3 concentrations show a similar pattern to the CO_2 concentrations. The variations are, however, somewhat larger as the higher temperatures in the low level exhaust cases reduce the relative humidity in the cages and reduce the rate of NH_3 generation, which leads to lower conentrations.

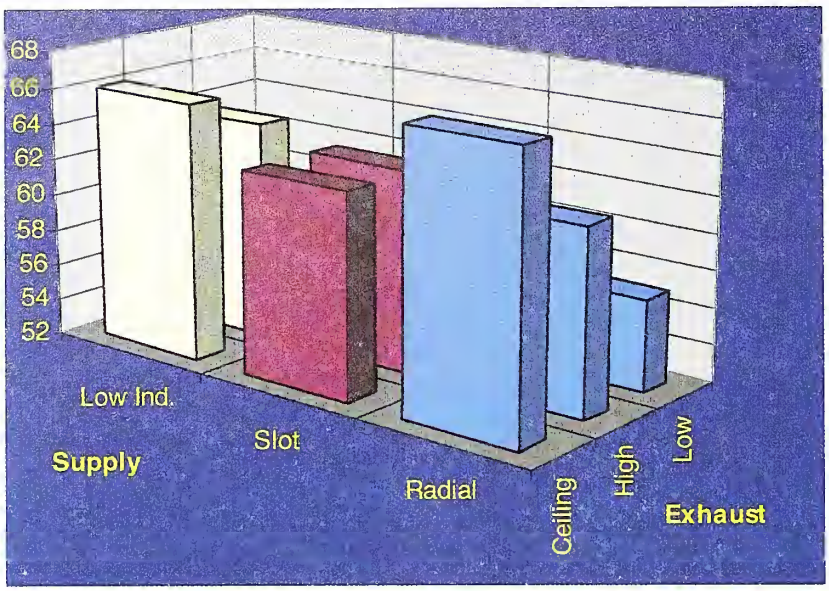


Figure 3.15 Comparison of Mean Cage Relative Humidity (percent)

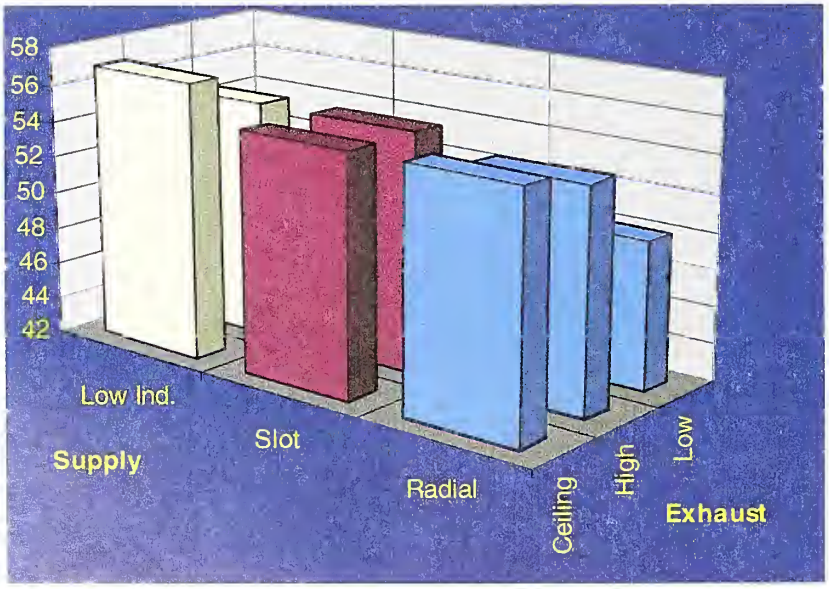


Figure 3.16 Comparison of Mean Breathing Zone Relative Humidity (percent)

Lower humidities in the low level exhaust cases are mainly due to the higher temperatures.

Two features are quickly apparent from these cases:

- low level exhausts produce higher temperatures in the room and cages; and
- low level exhausts produce the best in-cage ventilation (lowest CO_2 concentrations).

The low CO_2 concentrations seem to be due to the higher flow around the cages. Figures 3.17 and 3.18 show velocity vectors in a slice through the radial supply and the cage racks. For the ceiling level exhaust case (figure 3.17) the velocity vectors are barely visible around the cages, indicating very low flow. In figure 3.18 the low level exhausts case shows much larger velocity vectors representing much greater flow around the cages. This extra flow clearly helps ventilate the cages.

The ceiling level exhausts produce the lowest levels of CO_2 for the radial and low induction diffusers in the room breathing zone. This appears to be caused by the main airflow going through the cages towards the side walls at this height, whereas in the other cases there is more air coming from the side walls into the central region. This can be seen in figures 3.17 and 3.18 as well as in figures 3.19 and 3.20, which show the distribution of CO_2 concentration for the radial diffuser and ceiling and low level exhausts.

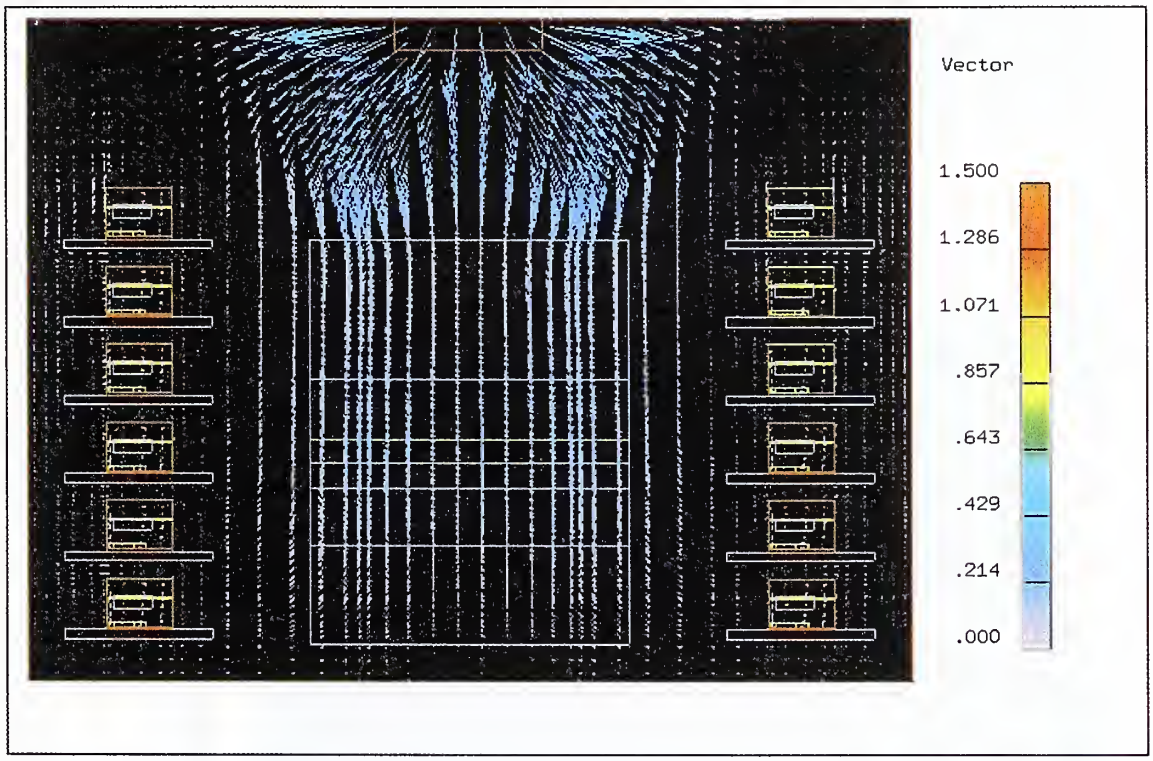


Figure 3.17 *Velocity Vectors through the Radial Diffuser with Ceiling Exhausts (basecase)*

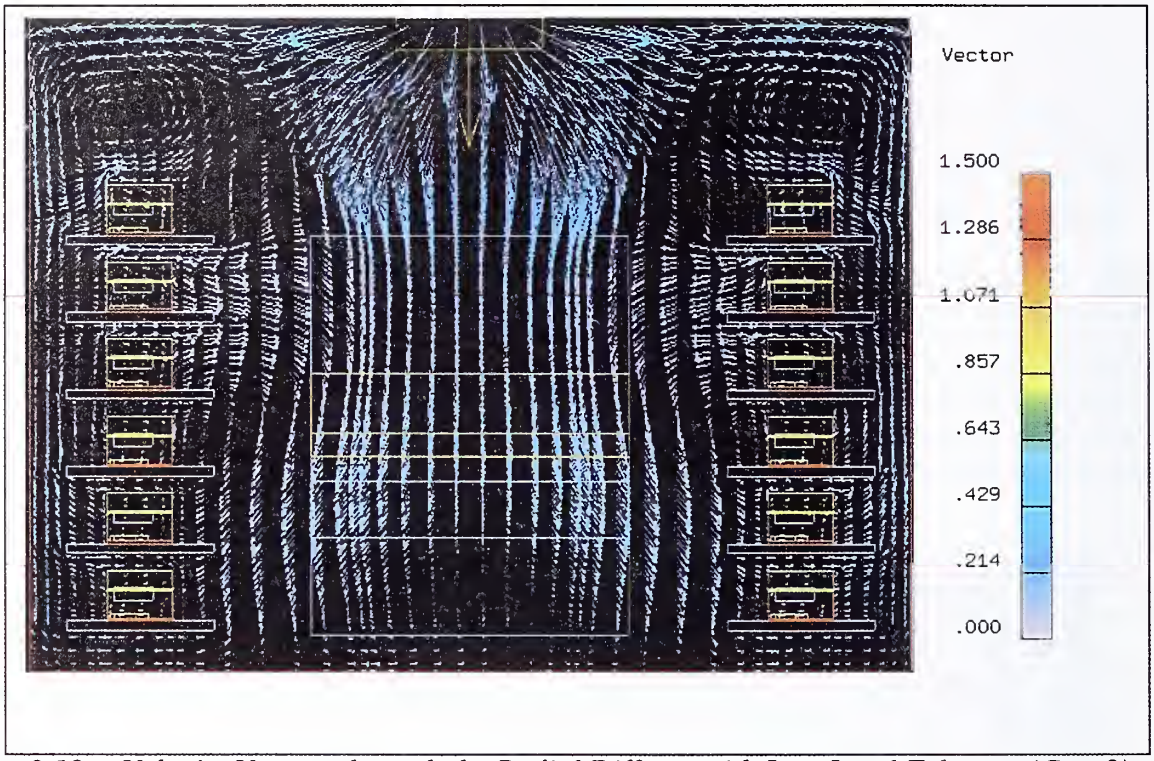


Figure 3.18 Velocity Vectors through the Radial Diffuser with Low Level Exhausts (Case3)

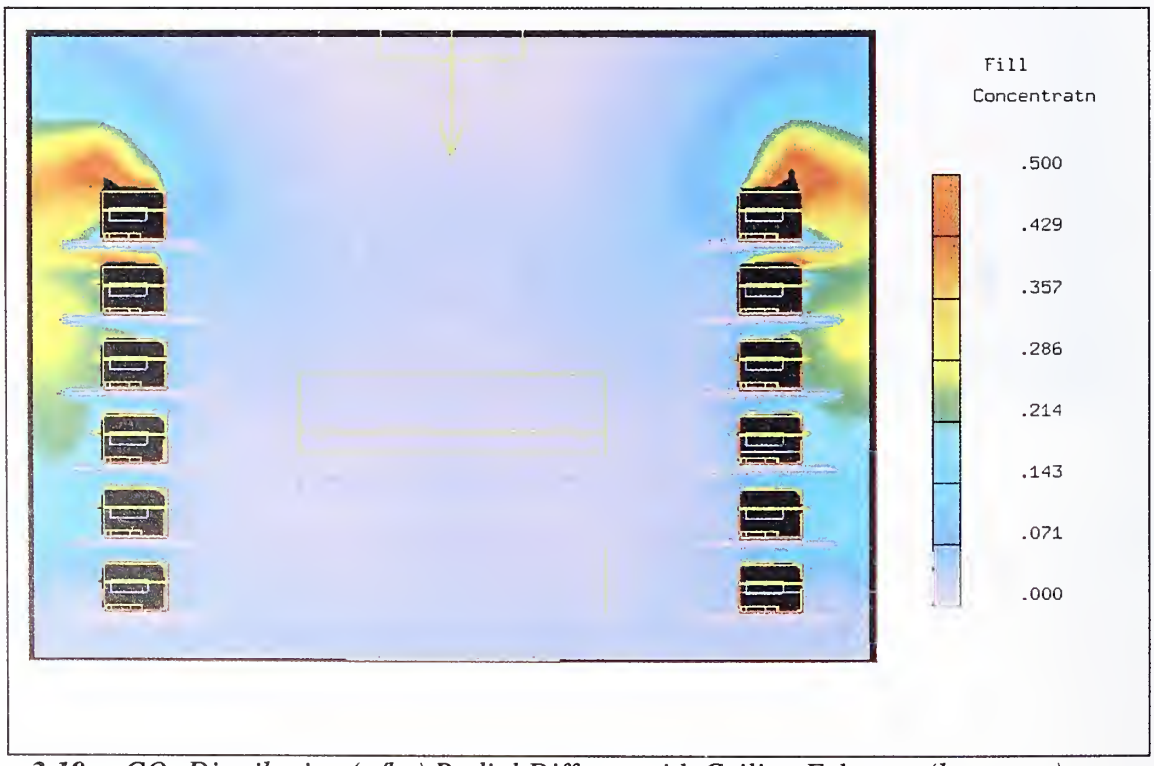


Figure 3.19 CO_2 Distribution (g/kg) Radial Diffuser with Ceiling Exhausts (basecase)

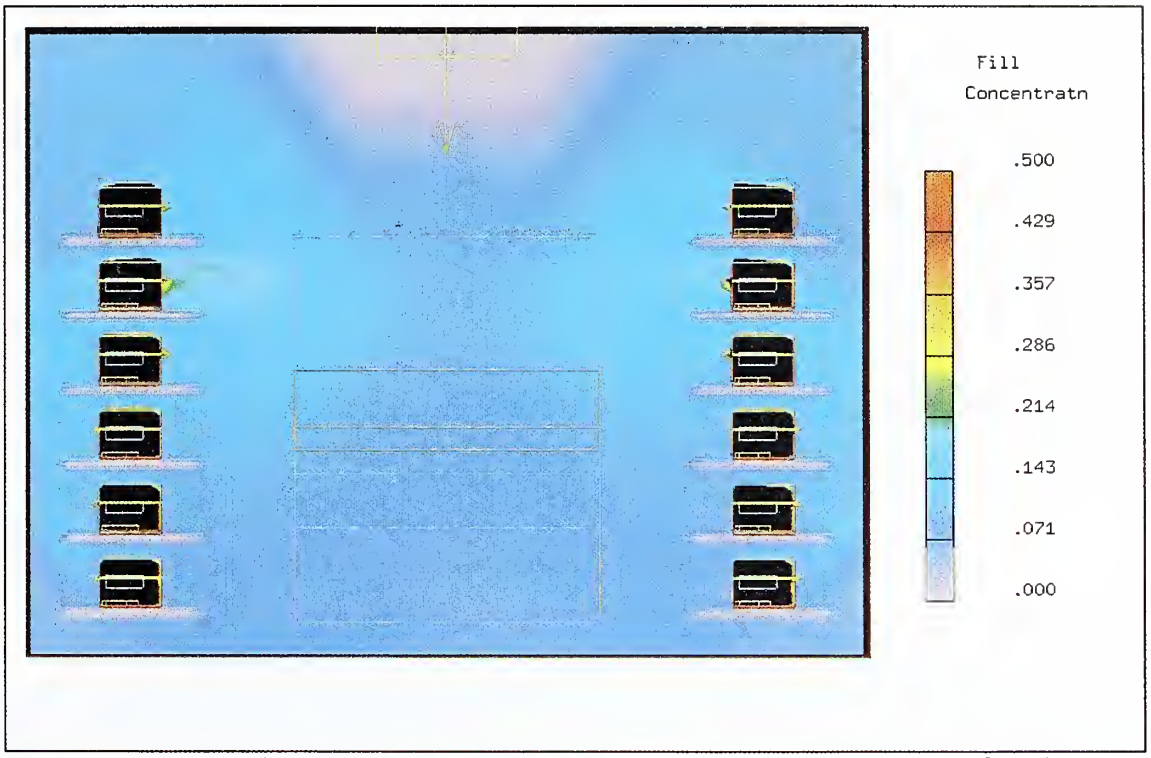


Figure 3.20 *CO_2 Distribution (g/kg) Radial Diffuser with Low Level Exhausts (Case3)*

Figures 3.21 and 3.22 show slices through the racks of cages for the radial diffuser with ceiling and low level exhausts. The low level exhausts clearly show lower CO_2 concentrations within the cages with less orange/red and more blue/green coloration. The variation in concentration is similar in both cases, with the highest values on the left and right edges of the three rack wall, and slightly lower concentrations in the center and on the tops of most of the racks.

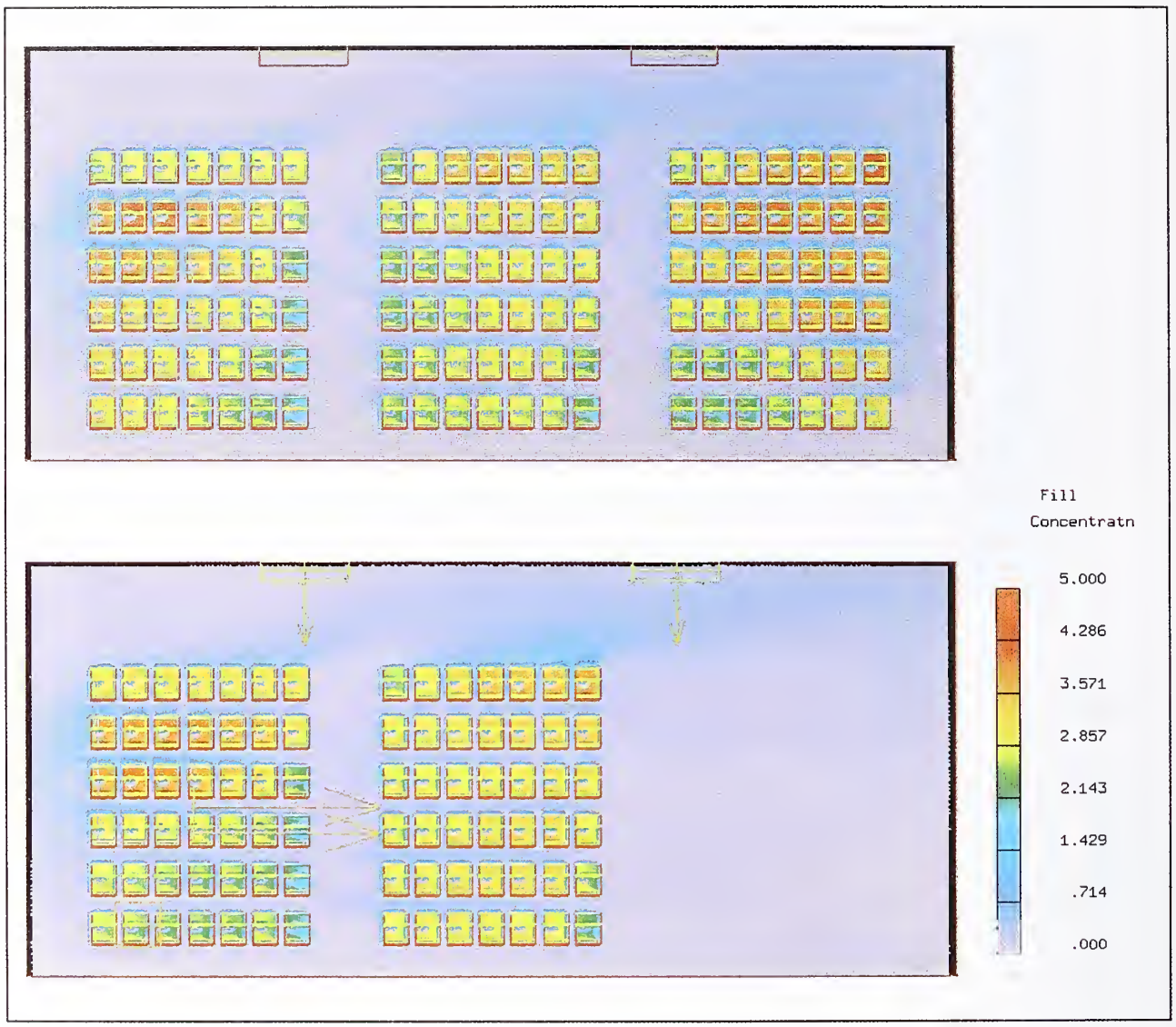


Figure 3.21 *CO_2 Concentration (g/kg), Radial Diffuser with Ceiling Exhaust (basecase)*

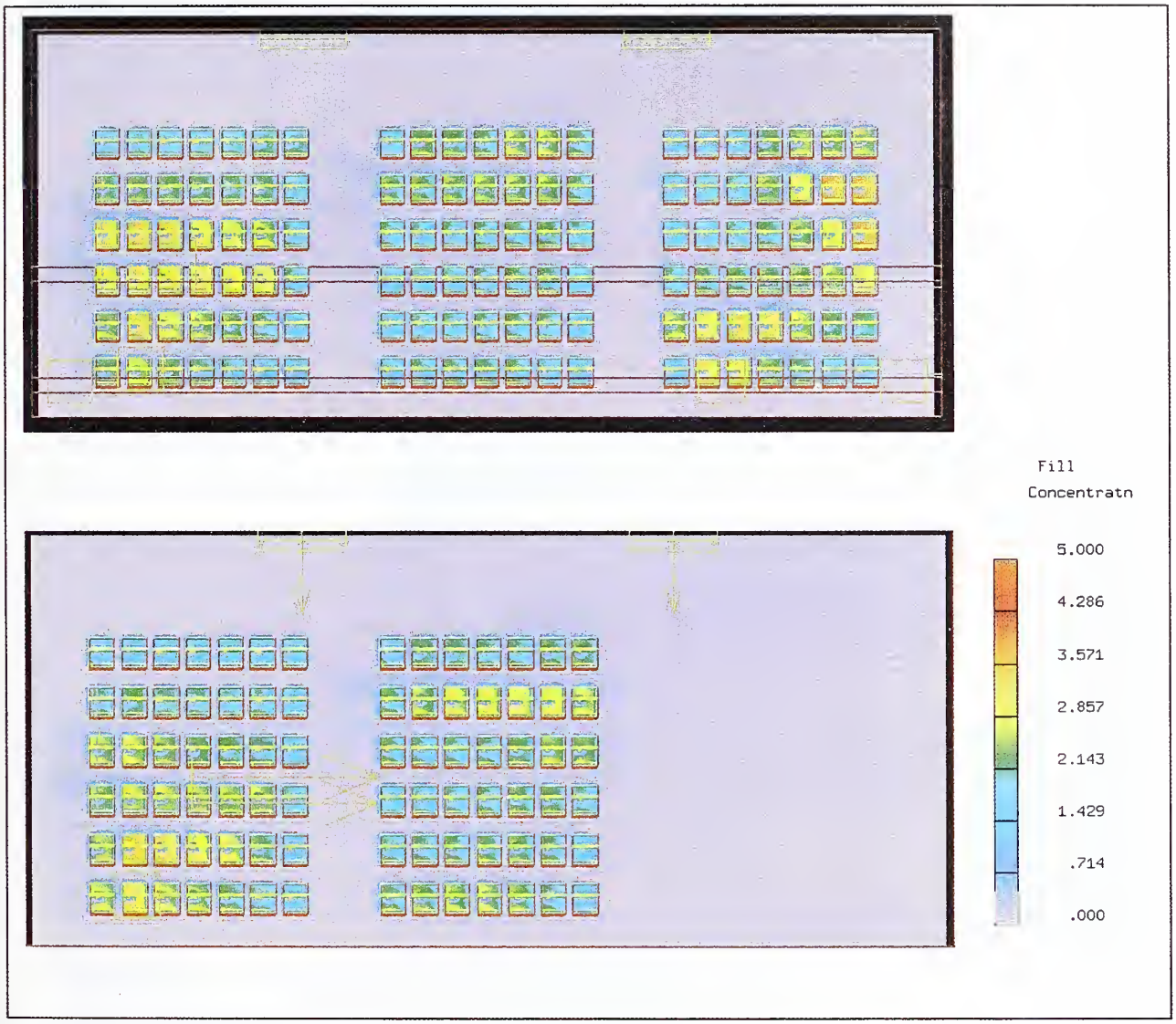


Figure 3.22 *CO_2 Concentration (g/kg), Radial Diffuser with Low Level Exhaust (Case3)*

The slot diffuser seems least sensitive to exhaust position. This is probably due to the slot diffuser creating much higher entrainment and mixing due to the higher supply air velocity and increased jet area.

The increase in temperature from the lower room ventilation efficiency, apparent in both the cages and the room for the low level exhausts, helps to keep the cage humidity levels low and reduces the NH_3 production.

Further variation in exhaust number and position was investigated in cases 37 to 42, 69 to 75 and 79 to 84. Examination of the data for these runs shows no obvious pattern emerging in cage and room ventilation. Case 40 (radial supply and four ceiling exhausts in the corners) seems to produce particularly low room breathing zone CO_2 and NH_3 concentrations, improving on the basecase values. However the other cases with four ceiling exhausts do not seem significantly better than the two ceiling exhaust cases.

3.1.2 Air Change Rate

Figures 3.23 to 3.28 show comparisons of temperature, CO_2 and NH_3 concentrations for both the cages and scientists' breathing zone for airflow rates between 5ACH and 20ACH. The plots show results for single density racks (42 cages) parallel to the walls (cases 9, 28-30) and double density racks (84 cages, cases 33, 62-64) perpendicular to the walls as well as a variation in change station design (84 cages, cases 65-68). All cases have low induction supplies and low level exhausts.

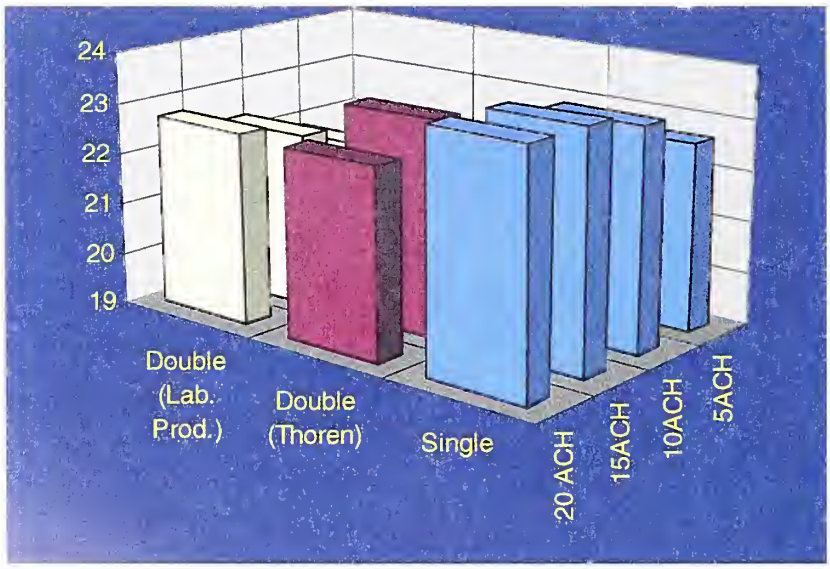


Figure 3.23 Comparison of Mean Cage Temperature (°C)

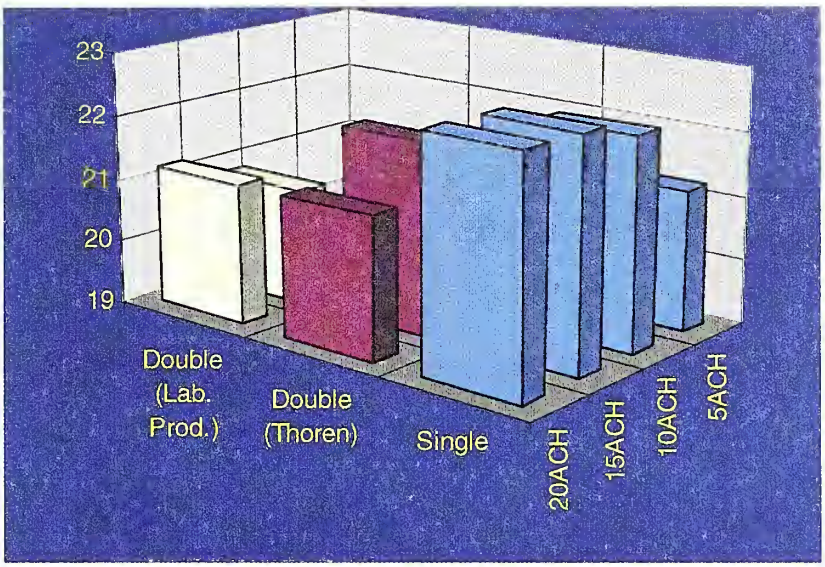


Figure 3.24 *Comparison of Room Breathing Zone Temperature (^oC)*

The cage temperatures vary very little in comparison with the variation in supply temperature (from 19.8 °C (68 °F) to 6.6 °C (44 °F)) and follow the trends shown in the breathing zone temperature. The slightly lower supply temperatures in the double density cases (more mice produce more heat to be extracted) lead to a small reduction in both room and cage temperatures compared with the single density racks.

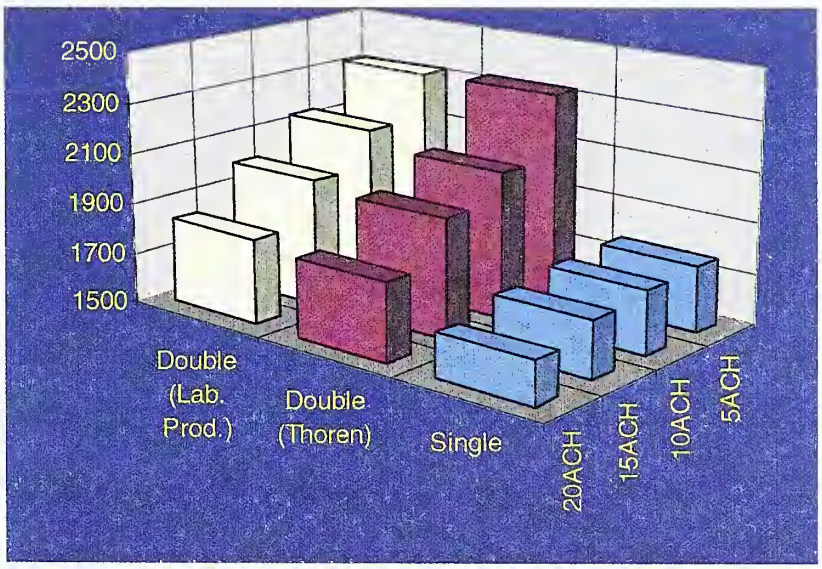


Figure 3.25 *Comparison of Mean Cage CO_2 Concentrations (ppm)*

Increasing the room ventilation rate does not have a large effect on the cage ventilation. Increasing the supply flow rate from 5 ACH to 20 ACH for single density racks parallel to the

walls reduces the CO_2 concentration from 1,764 ppm to 1,667 ppm, a reduction of only six percent. For the double density racks perpendicular to the walls the reduction is larger, but still only from about 2,300 ppm to 1,800 ppm (about 20 percent).

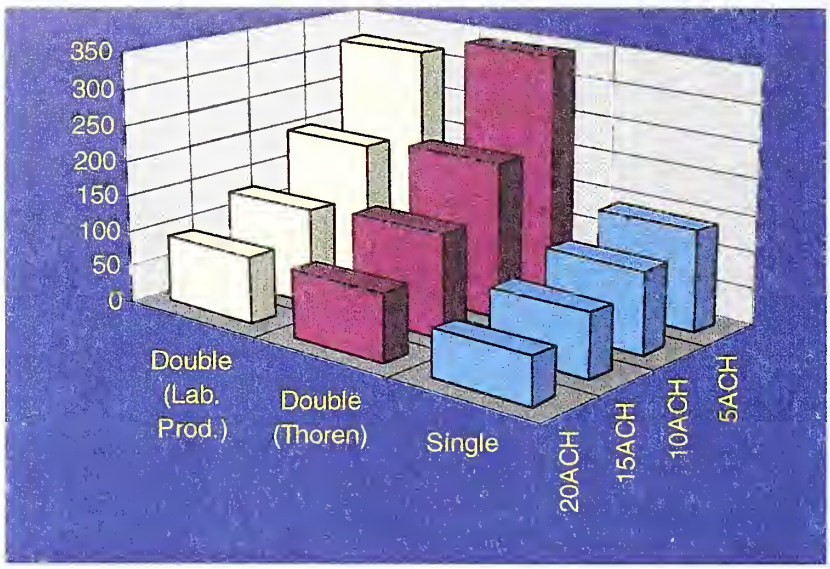


Figure 3.26 *Comparison of Room Breathing Zone CO_2 Concentrations (ppm)*

Increasing the room ventilation rate has a continuous beneficial effect on the room breathing zone ventilation (as measured by CO_2 and ammonia concentrations). For the single density racks parallel to the walls increasing the supply flow rate from 5 ACH to 20 ACH reduces the breathing zone CO_2 concentration from 140 ppm to 63 ppm, a decrease of 55 percent. For the double density racks perpendicular to the walls the reduction is even more dramatic, from over 300 ppm to 93 ppm (over 70 percent reduction) when the flow rate is increased from 5 ACH to 20 ACH. However, the "high" values of CO_2 concentration, of about 300 ppm above the background levels, are still significantly too low. The American Conference of Governmental Industrial Hygienists (ACGIH) recommends a threshold limit valve (TLV), time weighted average (TWA) of 5,000 ppm (9,000 mg/m^3) for carbon dioxide. ACGIH also recommended a Short Term Exposure Limit (STEL) of 30,000 ppm (54,000 mg/ m^3).

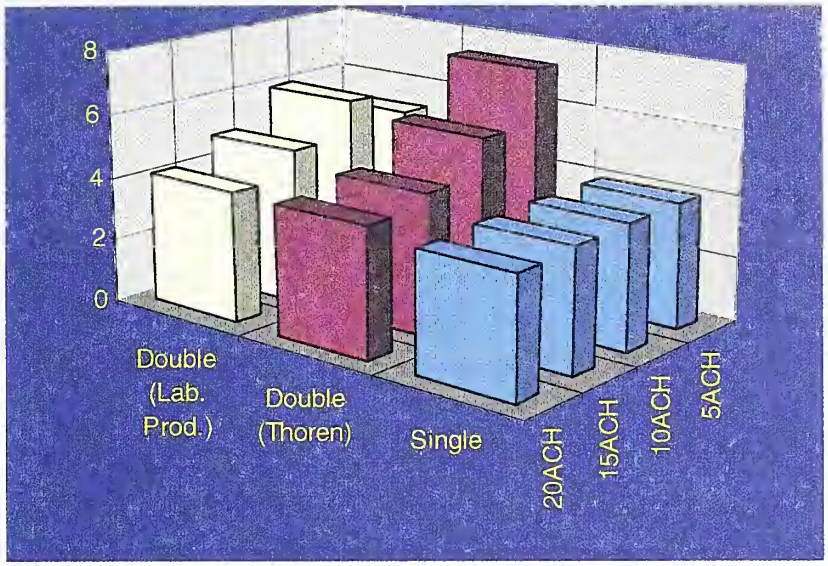


Figure 3.27 *Comparison of Mean Cage NH_3 Concentrations (ppm)*

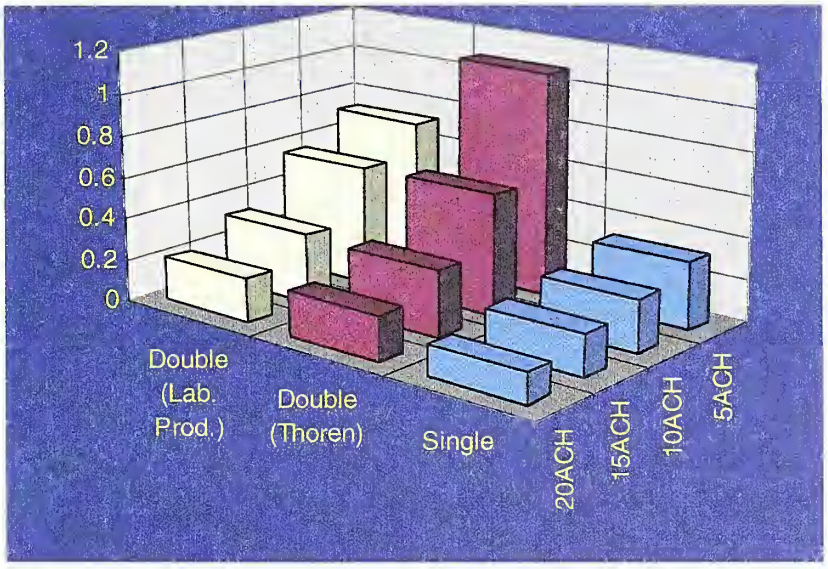


Figure 3.28 *Comparison of Mean Breathing Zone NH_3 Concentrations (ppm)*

The NH_3 concentrations follow the trends shown by the CO_2 concentrations. The 5 ACH NH_3 results are not directly comparable with those for the other flow rates. This is due to the extremely low supply discharge temperature 6.6 °C (44 °F) required to extract the heat produced by the mice and the change station, which required the moisture content of the air to be reduced compared to the other flow rates. the standard value used in the simulations represented well over 100 percent humidity. It is also recognised that this low temperature is difficult, if not impossible, to achieve in commercial heating and ventilation systems.

The results do indicate that the cages are not significantly better ventilated at higher flow rates. The rooms are better ventilated up to 20 ACH as would be expected because there is more fresh air available to dilute the gases produced by the mice.

The animal loading in the room is clearly significant. The 5 ACH supply rate in the room with single density cage racks (case 29) produces less than 50 percent of the room CO_2 concentration compared with the 5 ACH with the double density racks (cases 62 and 66). Since 10 ACH seems acceptable for day 4 NH_3 concentration in the cages of the double density rooms, and 5 ACH is acceptable for NH_3 concentrations in the cages of single density rooms, the airflow required in the room is best at 0.85 cfm (4.01e-4 m^3/s) per cage of five mice or 100g body weight of mice (see also section 3.2 below).

3.1.3 Change Station Design and Status

Cases 10 to 15 were run with the change station switched off and no heat generation or recirculated air. These should be compared with cases 1, 3, 4, 6, 7, and 9. Figures 3.29 to 3.32 show comparisons of CO_2 and NH_3 concentrations for the three supply diffusers with ceiling level exhausts and the Thoren change station in operation (on) and also with it present but not operating (off).

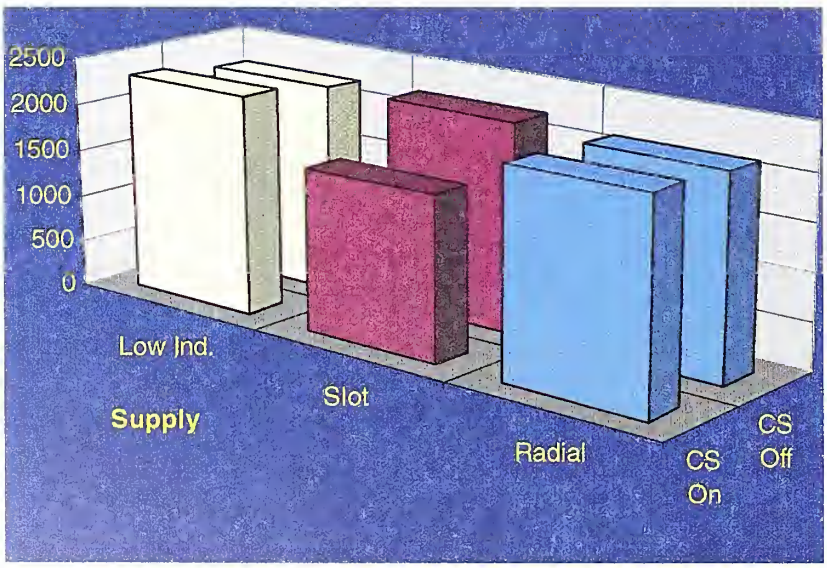


Figure 3.29 Comparison of Mean Cage CO_2 Concentrations (ppm)

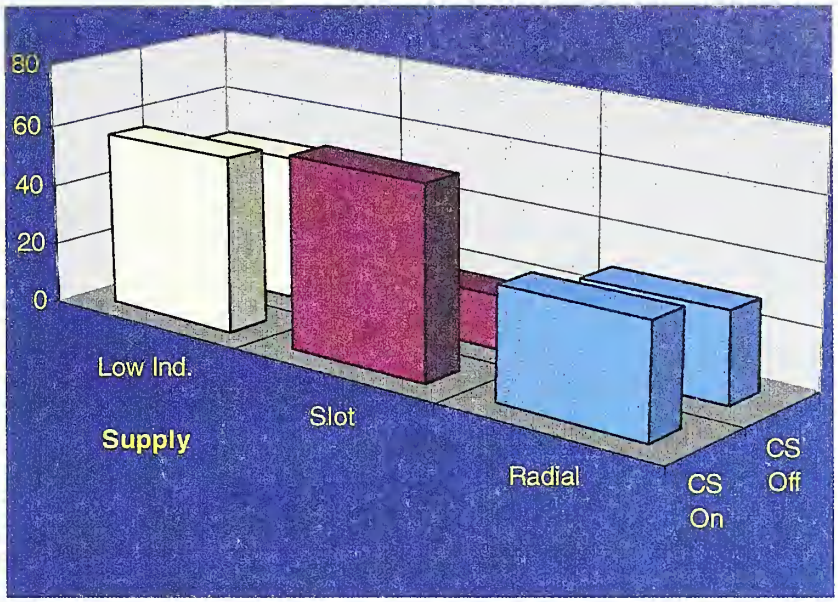


Figure 3.30 *Comparison of Mean Breathing Zone CO_2 Concentrations (ppm)*

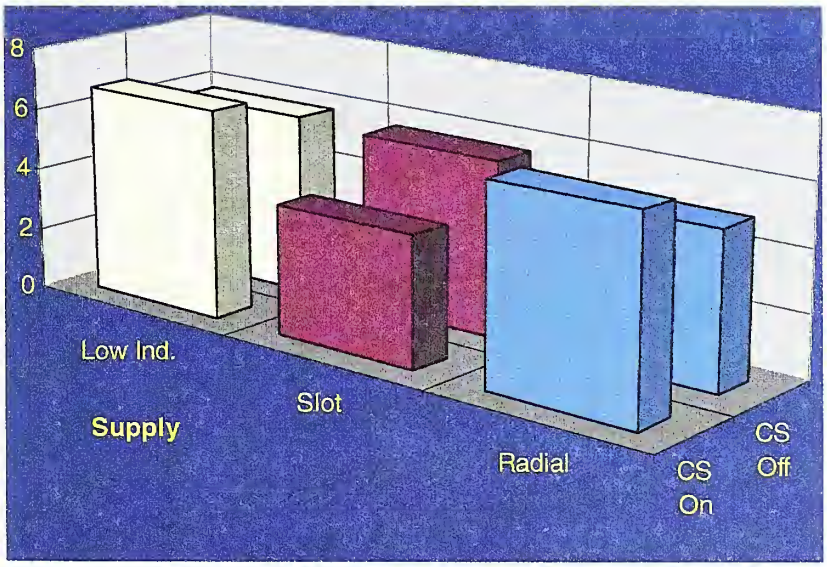


Figure 3.31 *Comparison of Mean Cage NH_3 Concentrations (ppm)*

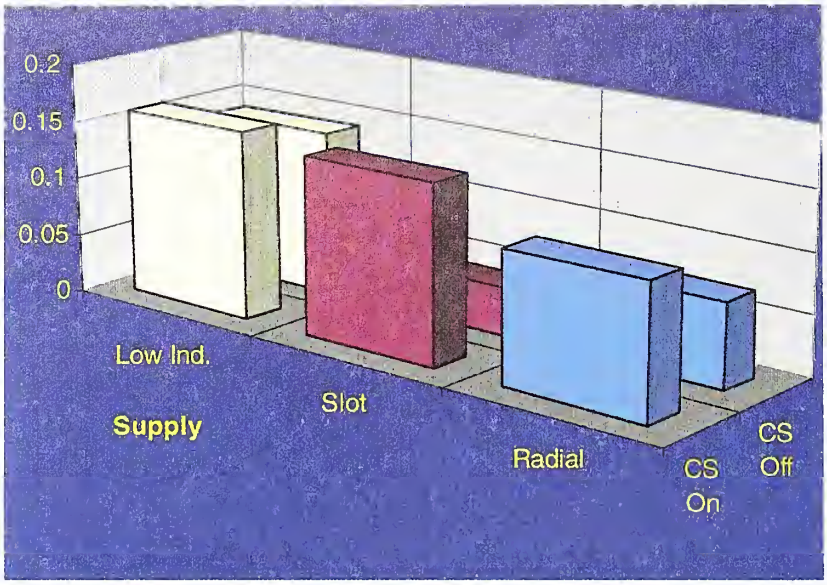


Figure 3.32 Comparison of Mean Breathing Zone NH_3 Concentrations (ppm)

Switching off the change station seems to decrease slightly the CO_2 and NH_3 concentrations in both the cages and the room for the radial and low induction supplies. The slot diffuser shows a small increase in both CO_2 and NH_3 concentrations in the cages, although the room values show a large decrease. This indicates the difficulty in making generalizations because the effect of making a change is very dependent on the case under consideration.

The change station produces a strong airflow upwards when active (see figure 3.33), which acts to mix dirty air from the cages with the fresh air from the supplies.

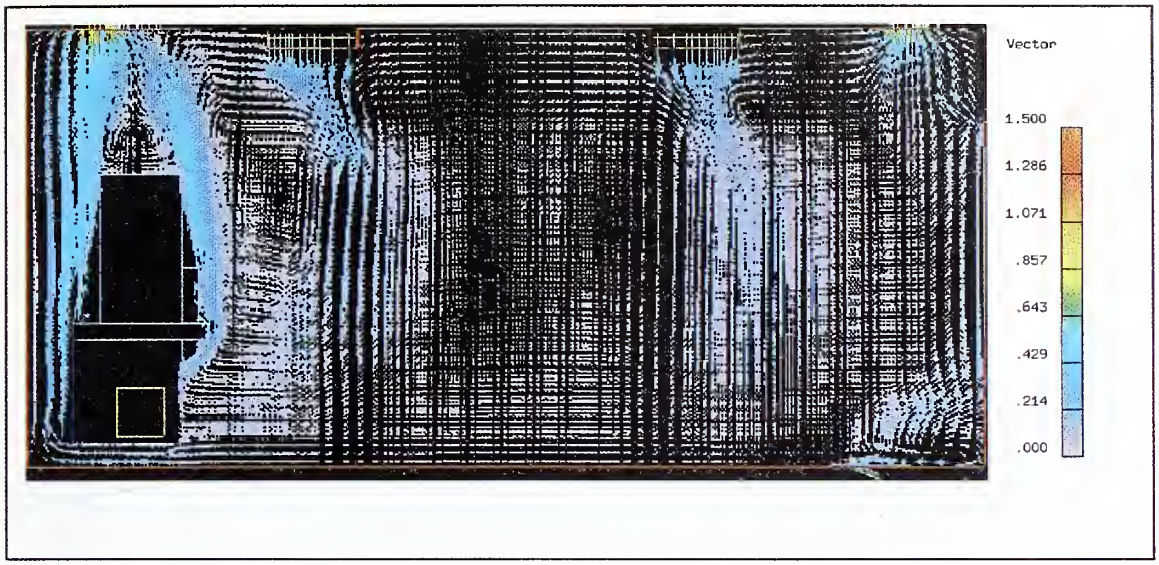


Figure 3.33 *Velocity Vectors on the Centerline for the Basecase Showing the Strong Upward Flow from the Change Station*

Cases 53 to 61 were run with an alternative change station design that had similar heat dissipation but a higher amount of recirculated air. This design seems to produce results very similar to those of the original change station.

It is interesting that two of the best performances for the room breathing zone CO_2 and NH_3 concentrations come out of this group of tests. Case 12 (slot supply, ceiling exhaust, change station off) and case 59 (slot supply, low level exhaust, alternative change station) produce the lowest CO_2 and NH_3 concentrations in the room. That there is no obvious link between these cases, and since other slot supply cases do not appear to be so good, this information serves to confirm that such complex airflows take place in animal rooms, it is difficult to predict how they will perform without detailed analysis.

3.1.4 Pressurization of Room relative to Corridor

Cases 16 to 18 were run with positive pressurization in the room instead of negative, with 100cfm (4.72e-2 m^3/s) air leaving rather than entering the room via the door. These cases should be compared with cases 1, 4 and 7, which are all cases with ceiling exhausts. Cases 45 to 47 varied the amount of air flowing in or out (50cfm in, 0cfm, and 50cfm out) of the door cracks and should be compared with cases 1 and 16.

Figures 3.34 to 3.37 show comparisons of CO_2 and NH_3 concentrations for different room pressurizations.

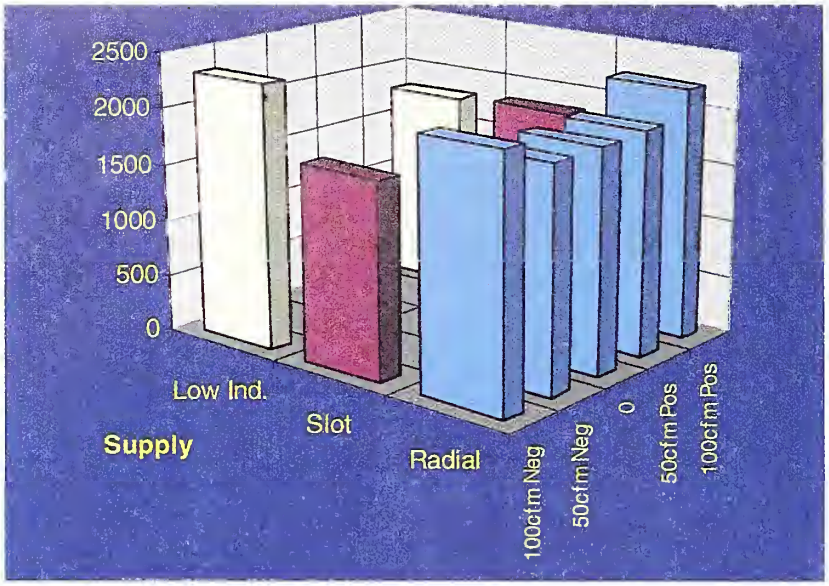


Figure 3.34 *Comparison of Mean Cage CO_2 Concentrations (ppm)*

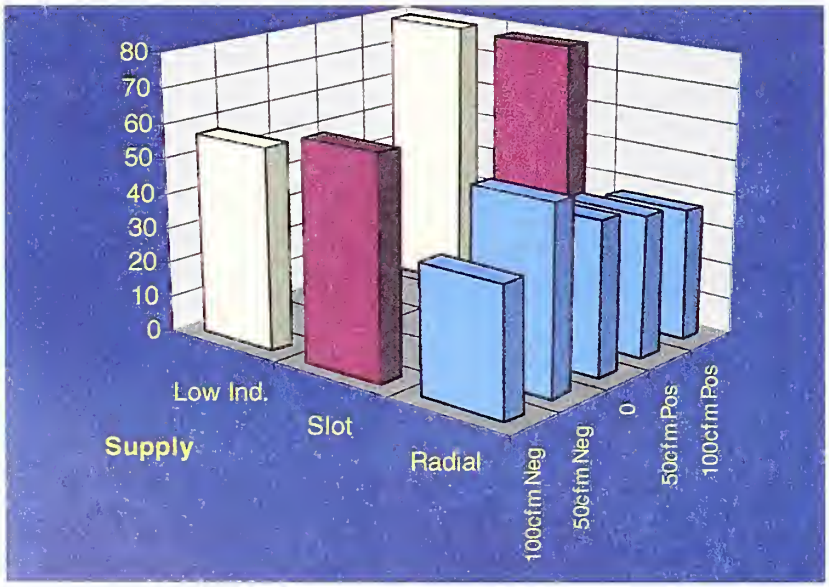


Figure 3.35 *Comparison of Mean Breathing Zone CO_2 Concentrations (ppm)*

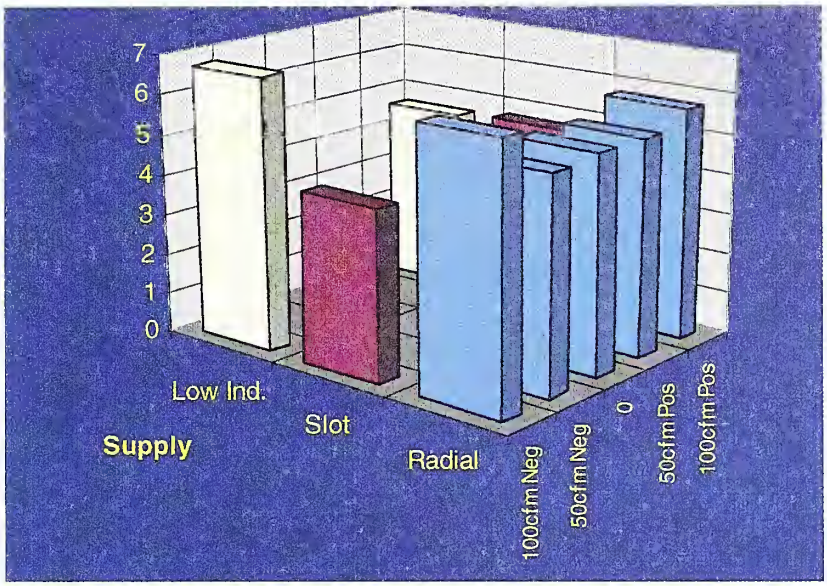


Figure 3.36 Comparison of Mean Cage NH_3 Concentrations (ppm)

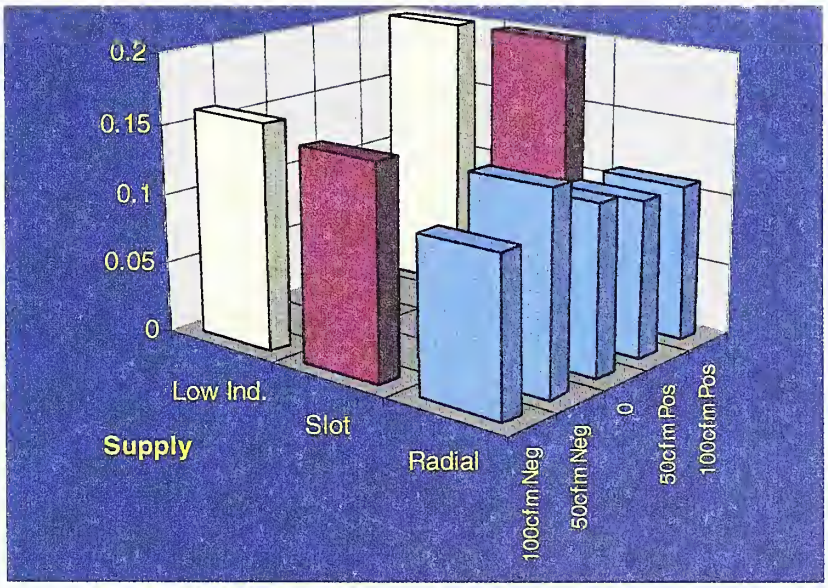


Figure 3.37 Comparison of Mean Breathing Zone NH_3 Concentrations (ppm)

100cfm inflow makeup air (negative pressurization) and 100cfm outflow makeup air (positive pressurization) represents around 18 percent of the supply diffuser flow rate at 15 ACH. Changing the direction of the makeup airflow has different effects on the CO_2 and NH_3 concentrations depending on the diffuser type. The radial diffuser, which was also run at 50 cfm positive and negative as well as neutral 0cfm, shows only small variations in both the room and cages.

The slot diffuser also shows little variation, with a small increase in cage concentrations and slightly larger increases in room concentrations, going from negative to positive pressurization. The low induction diffuser shows increases in room concentration but decreases in cage concentrations.

Again it is difficult to make a general recommendation. The effects seem small and dependant on the actual details of the configuration under study.

3.1.5 Orientation of Cage Racks in Room and Rack Grouping

Cases 19 to 24 were run with the five racks positioned perpendicular to the side walls rather than parallel to them. They should be compared with cases 1, 3, 4, 6, 7, and 9. This orientation removes the central open area in the room for the scientists as the racks overlap. However, data for the scientist's breathing zone are still reported although this is somewhat smaller. The analysis excluded a 0.15m (6") space around each cage.

Figures 3.38 to 3.41 show comparisons for the three diffuser types with ceiling level exhausts for single density racks parallel and perpendicular to the walls.

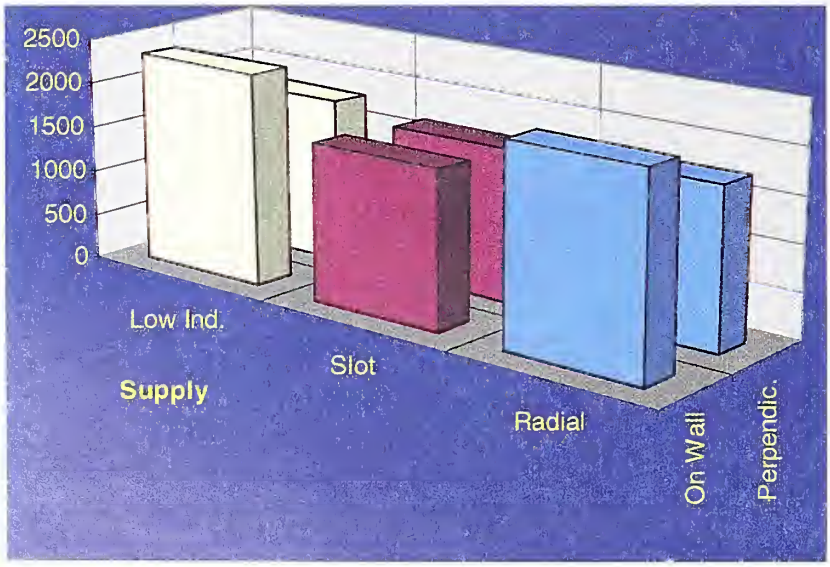


Figure 3.38 Comparison of Mean Cage CO_2 Concentrations (ppm)

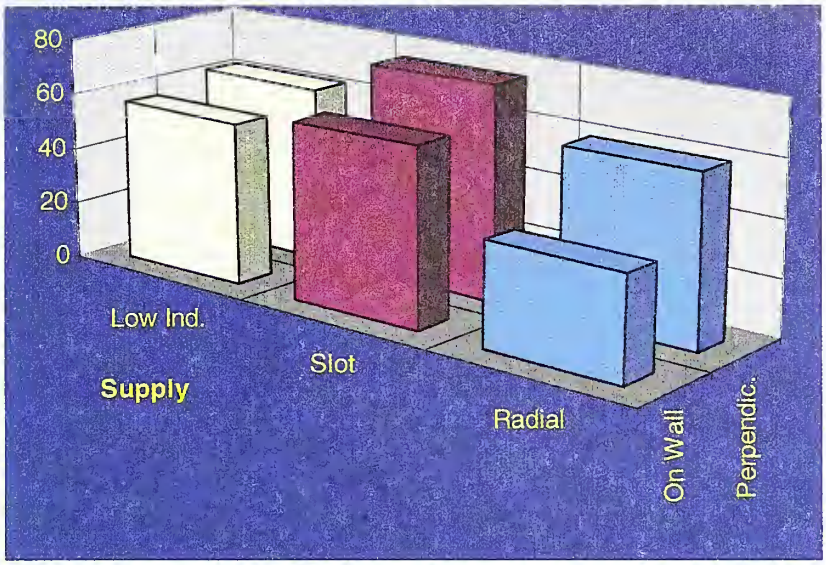


Figure 3.39 *Comparison of Mean Breathing Zone CO_2 Concentrations (ppm)*

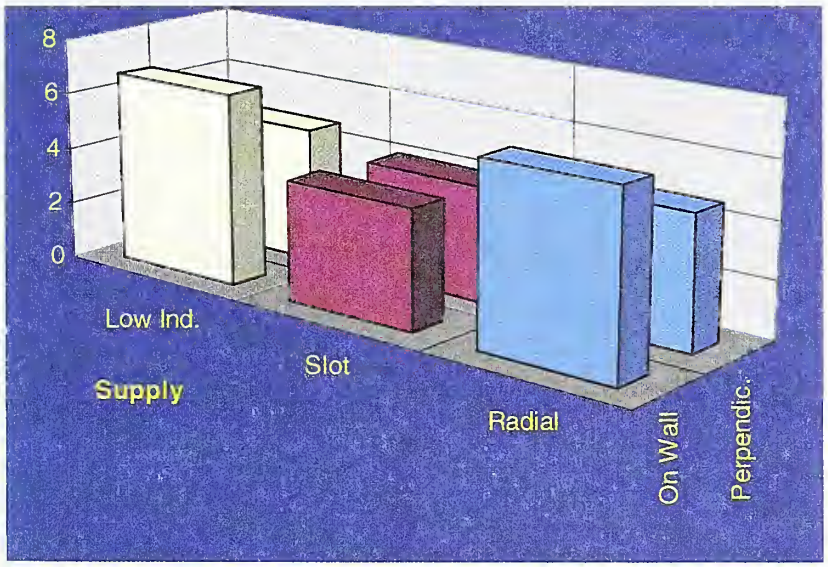


Figure 3.40 *Comparison of Mean Cage NH_3 Concentrations (ppm)*

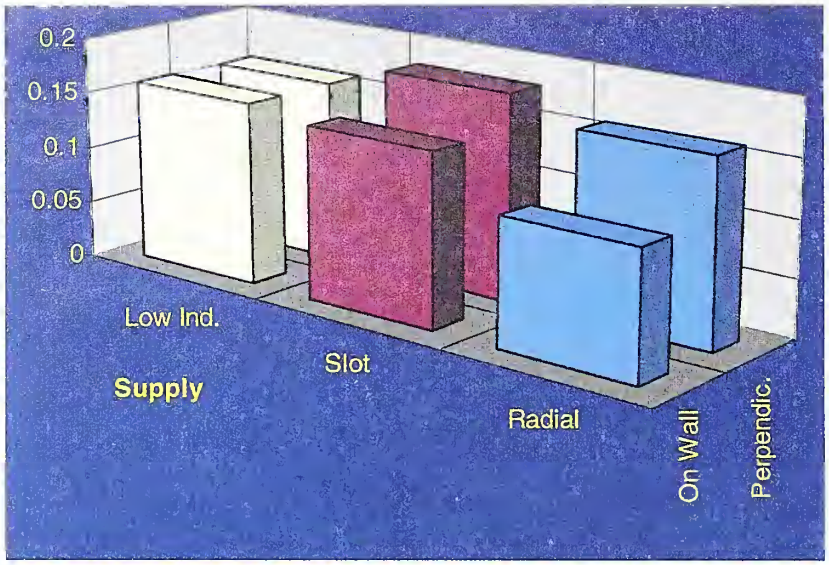


Figure 3.41 *Comparison of Mean Breathing Zone NH_3 Concentrations (ppm)*

The radial and low induction diffusers show a reduction in cage CO_2 and NH_3 concentrations in the cages with clearly better ventilation through the racks (and cages) in this perpendicular orientation. The in-room breathing zone values show similar or slightly increased CO_2 and NH_3 concentrations.

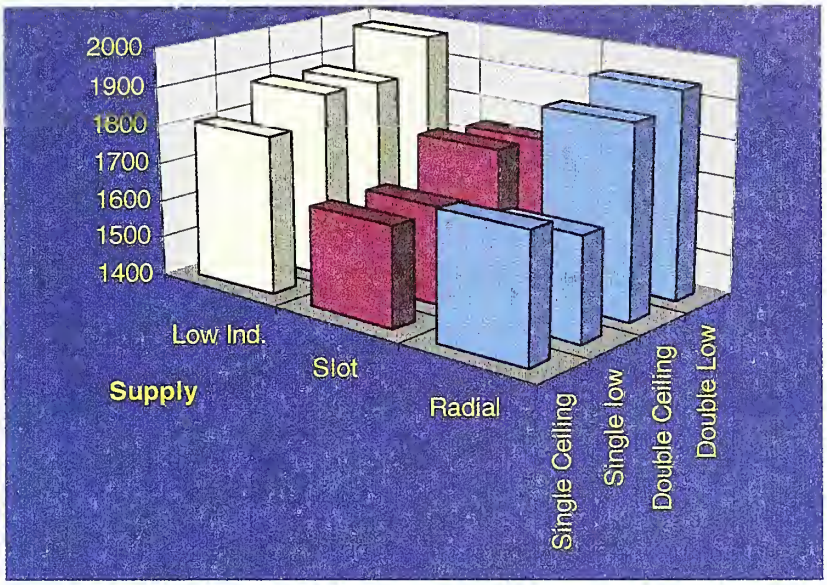
Cases 48 to 52 were run with different positions for the change station (swapped with particular racks) and cases 90 to 92 were run with all five racks positioned on one wall rather than split two on one wall and three on the other. Again, variations in CO_2 and NH_3 concentrations for both the cages and the room are small.

In conclusion, apart from the improvement in cage ventilation for the radial and low induction diffusers when the racks are perpendicular to the walls, no particular advantage or disadvantage in any orientation or rack layout can be seen.

3.1.6 Density of Cages

Cases 31 to 36 were run with double the number of cages on each rack. This meant a total of 420 cages were present in the room. To provide easy access to all the cages it was necessary to use only rack orientations that were perpendicular to the side wall (i.e., into the room not parallel to the side walls).

Figures 3.42 to 3.45 show comparisons of CO_2 and NH_3 concentrations for the three supply diffuser types with ceiling and low level exhausts.



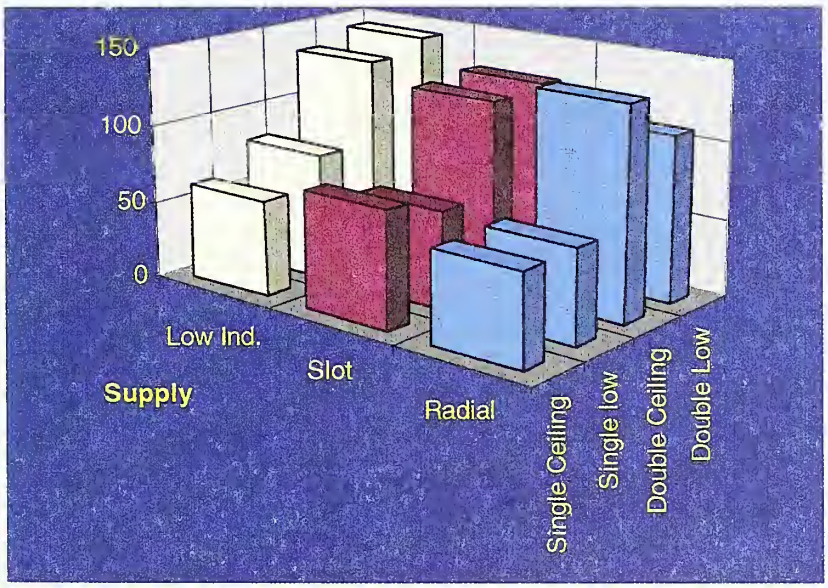


Figure 3.43 *Comparison of Mean Breathing Zone CO_2 Concentrations (ppm)*

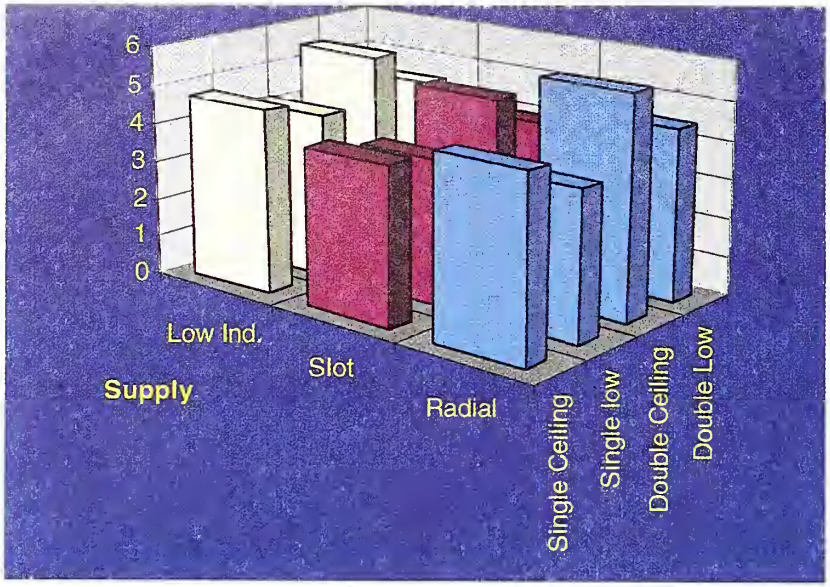


Figure 3.44 Comparison of Mean Cage NH_3 Concentrations (ppm)

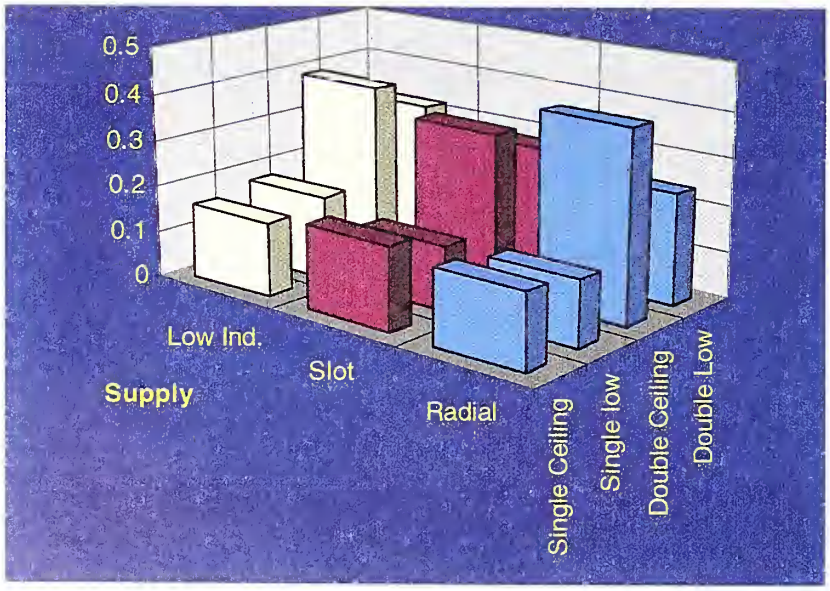


Figure 3.45 Comparison of Mean Breathing Zone NH_3 Concentrations (ppm)

The in-cage values for these runs are not very different from the single density rack. The in-room breathing zone values are much higher. They are about double the CO_2 and NH_3 concentrations of the single density (compare with cases 19 to 24).

Cases 62 to 68 were also double density runs with variation in air change rate. These cases were discussed in section 3.1.2. These cases were the worst, run with 5 ACH producing very high NH_3 concentrations in the scientist's breathing zone.

Cases 87 to 89 were run with a reduced number of cages on each rack (28 instead of 42) for each supply type with low level exhausts. Apart from the slight reduction in room breathing zone CO_2 and NH_3 concentration, no particular changes can be seen. The radial supply seems the best in the room and the low induction the worst, as is the case with the normal racks (42 cages).

3.1.7 Side Cracks of Cages Sealed instead of Open

Where the bonnet filter top sits on the bottom of the microisolator cage the CFD model allowed for an imperfect fit, i.e., air could enter or leave the cage via small cracks. To investigate this effect, three cases were run with sealed cracks, i.e., no air could enter or leave the cages except through the filter.

Cases 25 to 27 were run with sealed cages instead of leaky ones for the three supply types and ceiling exhausts (compare with cases 1, 4 and 7).

Figure 3.46 shows the comparison of in-cage mean temperatures and shows very little change difference between the normal cage model and the fully sealed one.

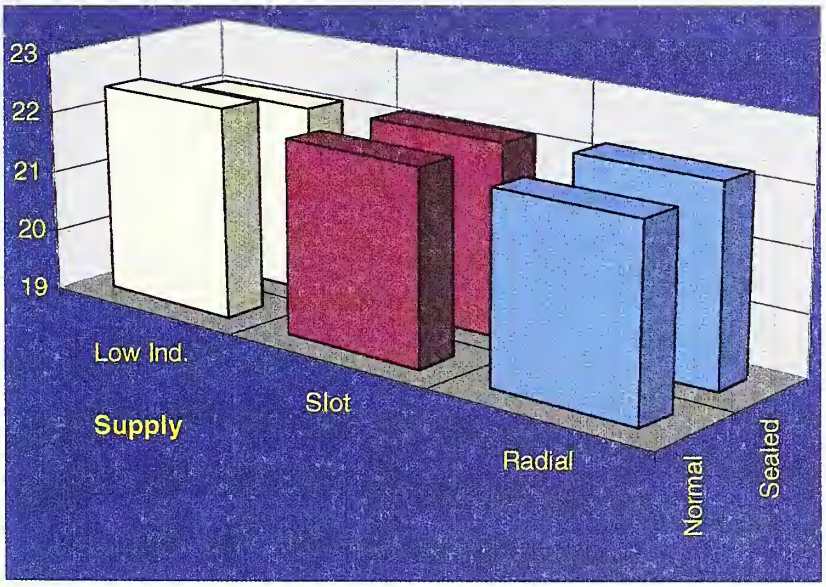


Figure 3.46 *Comparison of Mean Cage Temperatures (°C)*

Figures 3.47 to 3.50 show comparisons of CO_2 and NH_3 concentrations for the three supply diffuser types with ceiling exhausts for the normal and sealed cage.

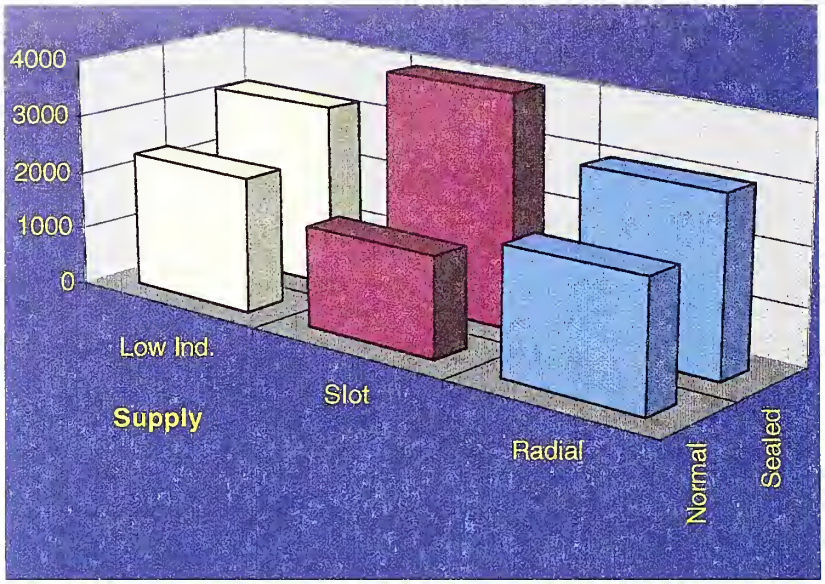


Figure 3.47 Comparison of Mean Cage CO_2 Concentrations (ppm)

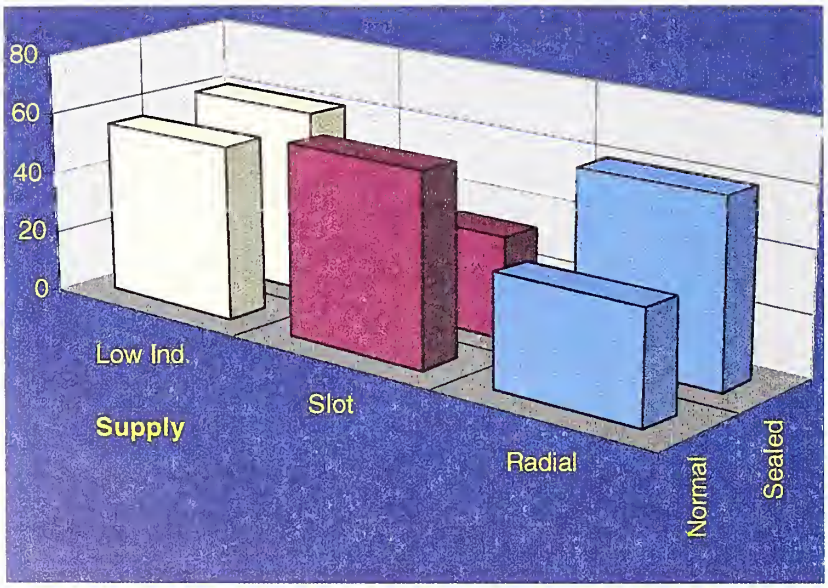


Figure 3.48 Comparison of Mean Breathing Zone CO_2 Concentrations (ppm)

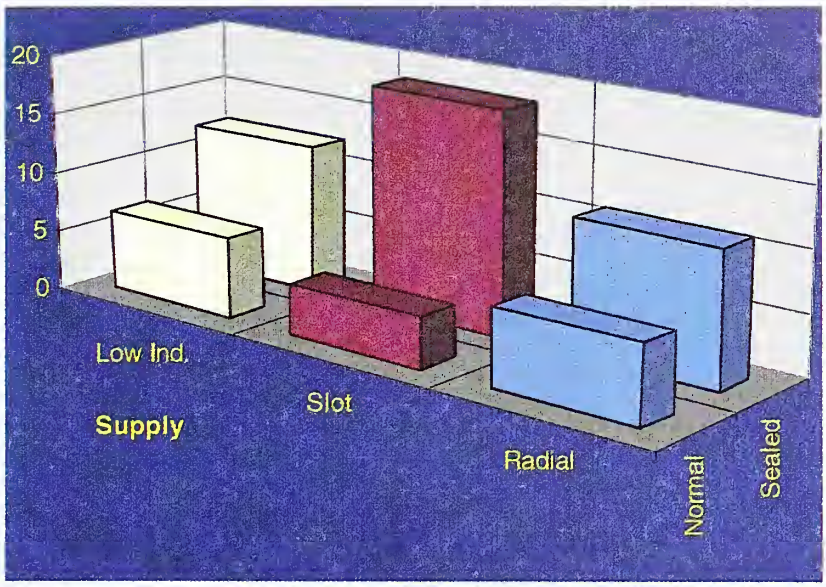


Figure 3.49 *Comparison of Mean Cage NH_3 Concentrations (ppm)*

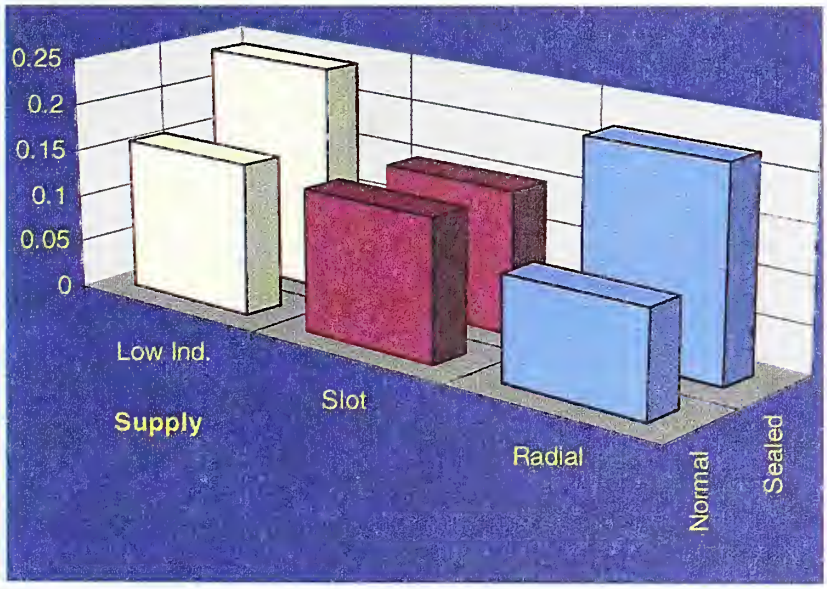


Figure 3.50 *Comparison of Mean Breathing Zone NH_3 Concentrations (ppm)*

The cages show large increases in both CO_2 and NH_3 concentrations. The room values show little variation in CO_2 concentration but an increase in NH_3 concentration. This is due to the increased cage relative humidities (see figure 3.51) which causes an increased NH_3 generation.

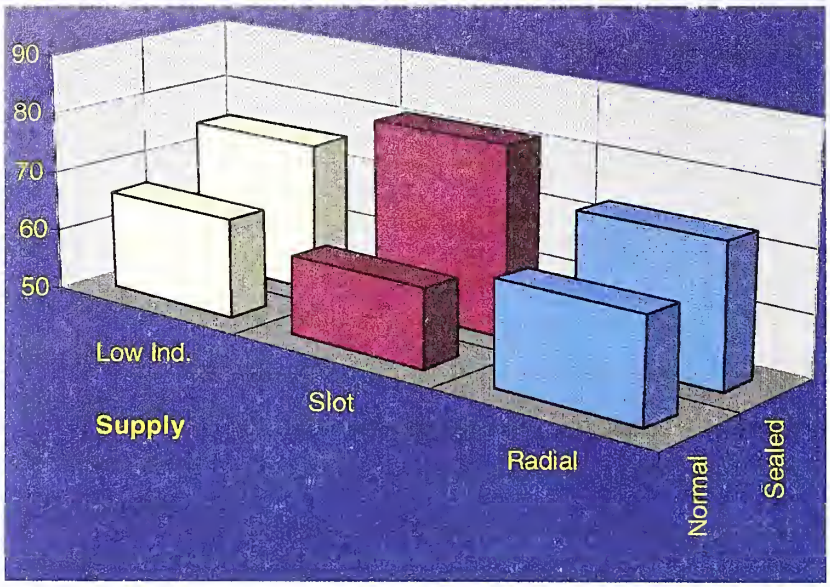


Figure 3.51 Comparison of Mean Cage Relative Humidity (percent)

Although the ventilation of the cages is much worse, which leads to the high concentrations, the temperatures within the cages are not noticeably different. This is partly to be expected, as the CFD model of the mice is a constant temperature model. Even if there was no ventilation of the cages, the temperature in the cage cannot exceed the 30.0 °C (86.0 °F), which is the surface temperature of the mice.

3.1.8 Room Width

Cases 76 to 78 were run with an increased room width 4.26m (14' 0") instead of the original width of 3.66m (12' 0"), with ceiling exhausts for the three supply types. They should be compared with cases 1, 4 and 7. Figures 3.52 to 3.55 show comparisons of CO_2 and NH_3 concentrations.

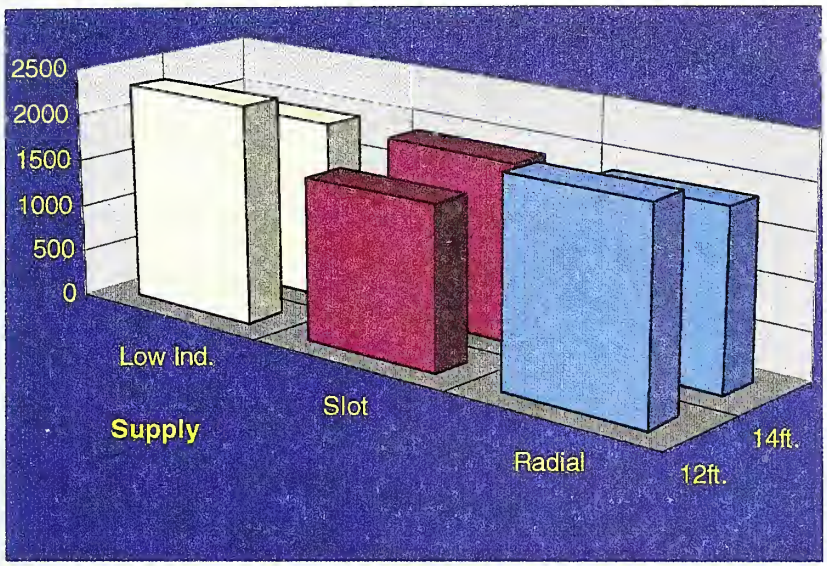


Figure 3.52 *Comparison of Mean Cage CO_2 Concentrations (ppm)*

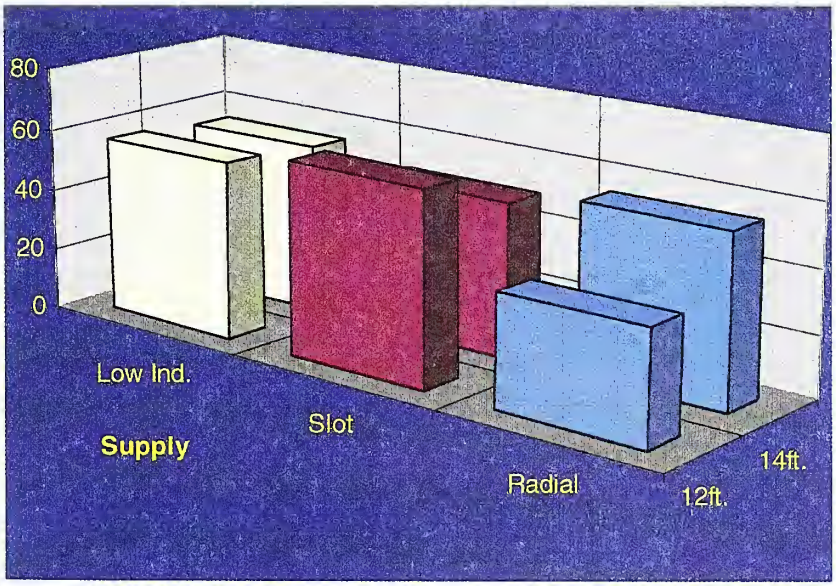


Figure 3.53 *Comparison of Mean Breathing Zone CO_2 Concentrations (ppm)*

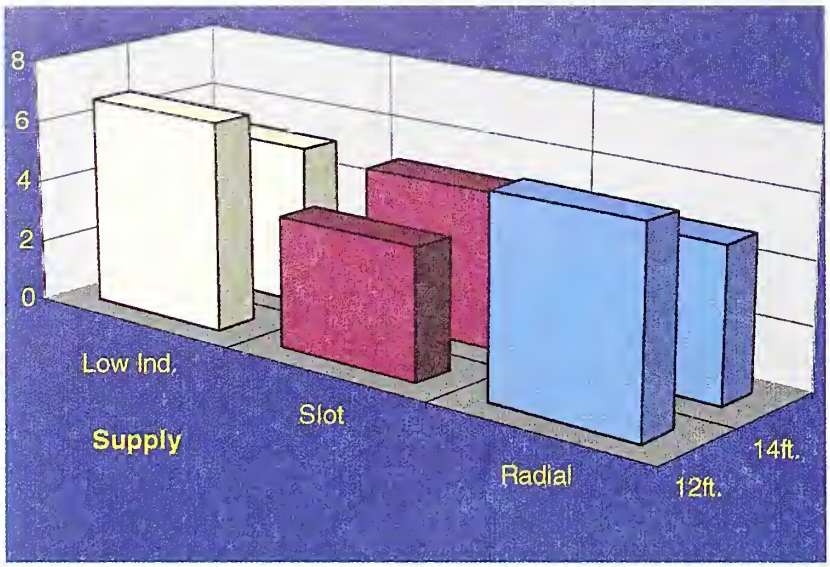


Figure 3.54 Comparison of Mean Cage NH_3 Concentrations (ppm)

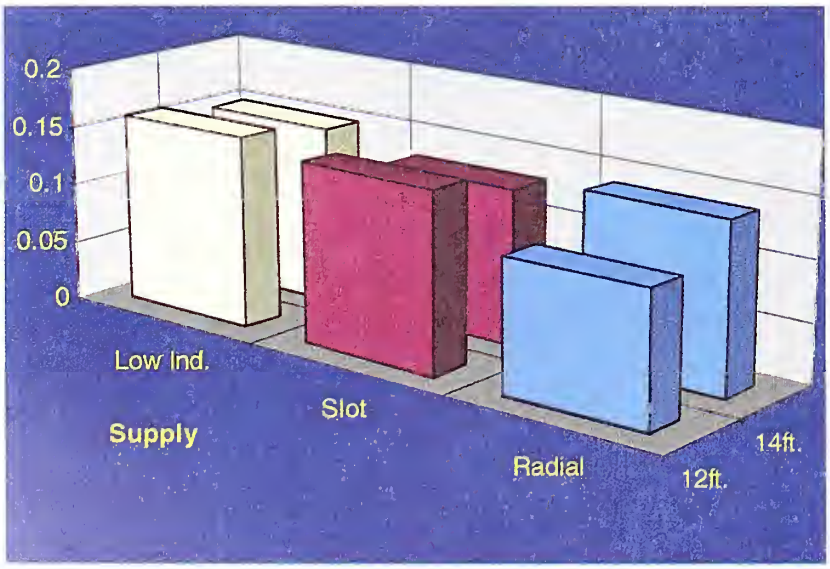


Figure 3.55 Comparison of Mean Breathing Zone NH_3 Concentrations (ppm)

The in-cage values are slightly reduced for both the radial and low-induction supply diffusers, while the room values show little change or some increase. As is often the case, improving the cage ventilation seems to degrade the room performance.

3.1.9 Supply Temperature

The experimental data for the generation of NH_3 indicate that NH_3 is produced at a higher rate when the relative humidity is high. As the relative humidity decreases with increasing

temperature it was expected that the NH_3 concentrations in the cages and room would be related to the supply temperature.

Figures 3.56 and 3.57 show the cage and room temperatures plotted against the supply temperature. As expected, the higher the supply temperature the higher the cage and room temperatures, although there is a wide variation as was noted previously. The choice of exhaust location has a strong influence on the room and cage temperature.

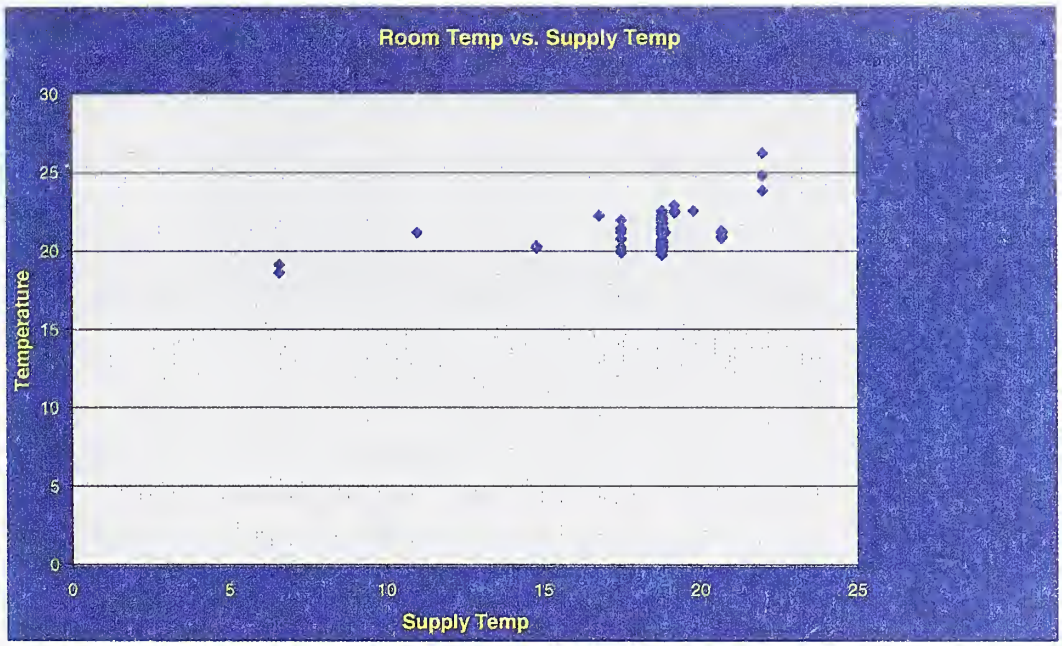


Figure 3.56 *Room Breathing Zone Temperature vs. Supply Discharge Temperature*

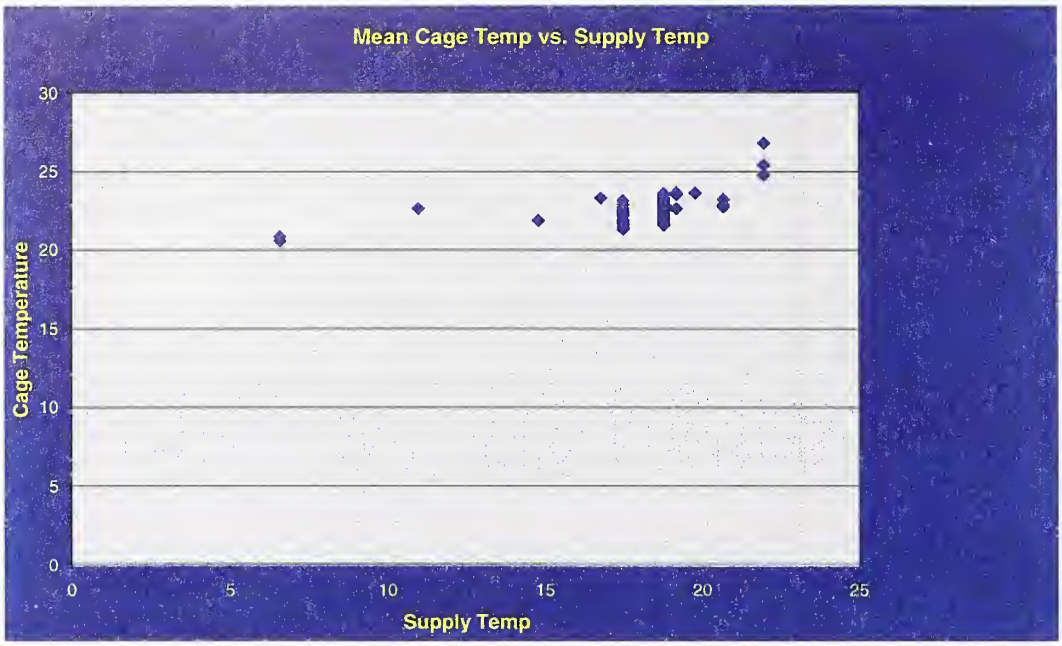


Figure 3.57 Mean Cage Temperatures vs. Supply Discharge Temperature

Figures 3.58 and 3.59 show the cage and room NH_3 concentrations on day 4 plotted against supply relative humidity (RH). The cage values show no notable trend with quite a wide variation at the standard supply RH of 61 percent. However, even though there is some scatter in the data, the room NH_3 concentration plot shows a clear trend to higher values at higher supply RH.

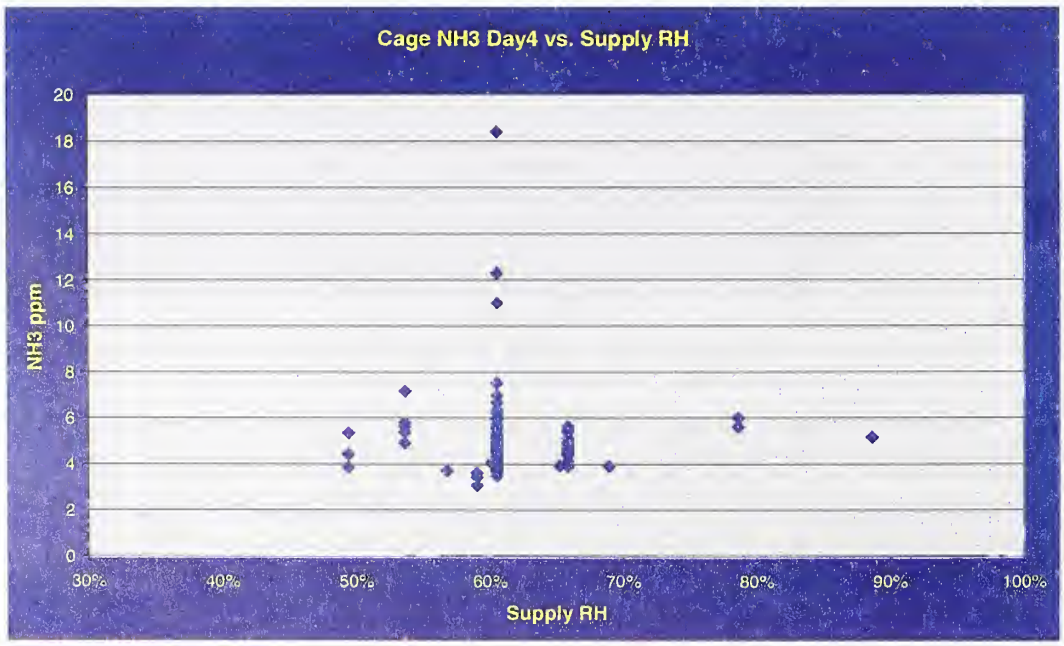


Figure 3.58 Cage NH_3 Concentration vs. Supply Relative Humidity

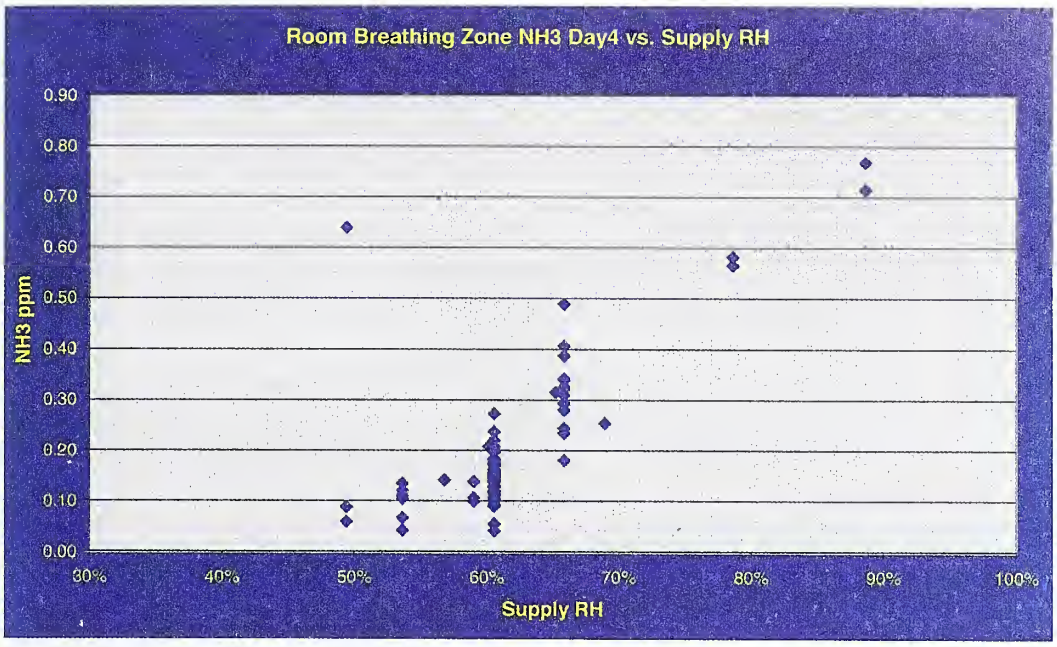


Figure 3.59 *Room Breathing Zone NH_3 Concentration vs. Supply Relative Humidity*

Cases 99 to 101 were run with a supply temperature of 22.2 °C (72.0 °F). Case 99 was the same as the basecase (radial supply ceiling exhaust), case 100 was the same as case 3 (radial supply low level exhaust) and case 101 was the same as case 66 (low induction supply, low level exhaust, 5 ACH). These cases were run to investigate the effect of increased temperatures in the room, in particular the reduction of relative humidity and NH_3 generation that should result.

Raising the supply temperature for these cases produces an increase in both room and cage temperature as shown in table 3.02

Table 3.02 Comparison of Temperatures °C (°F)

	Case 01	Case 99	Case 03	Case 100	Case 66	Case 101
Room BZ	20.3 (68.5)	23.9 (75.0)	22.7 (72.9)	24.8 (76.6)	18.6 (65.5)	26.2 (79.2)
Cage Mean	22.1 (71.8)	24.8 (76.6)	23.4 (74.1)	25.4 (77.7)	20.6 (69.1)	26.8 (80.2)
Cage Max	23.0 (73.4)	25.7 (78.3)	24.6 (76.3)	26.8 (80.2)	21.9 (71.4)	28.3 (82.9)

Cases 99 and 100 represent an increase of 3.2 °C (5.8 °F) in the supply temperature and produce an increase of around 2.5 °C (4.5 °F) in both room and cage temperature. Case 101 represents an increase of 15.4 °C (27.7 °F) in the supply temperature. This raises the room and cage temperature by nearly 8.0 °C (14.4 °F). The maximum temperature in a cage is increased to around 28.0 °C (82.4 °F). Although it is high, is still likely to be more than acceptable to the mice.

Case 99 produces an improvement in NH_3 concentration in the room of nearly 50 percent and nearly 30 percent in the cage.

Cases 100 and 101 do not produce the same level of improvement as the original cases 3 and 66, which already have very low humidity values (below the 61 percent minimum from the experimental data), and so the reduction in humidity does not produce a lower NH_3 generation rate.

To further investigate the effect of increasing supply temperature (without re-running all 101 cases) the data was "post-processed" by adding 3.2 °C (5.8 °F) to the mean temperature for each cage. This is equivalent to raising the supply temperature by approximately 4.0 °C (7.2 °F).

Figures 3.60 and 3.61 show the resulting bar charts for the day 4 cage and room NH_3 concentrations together with the original data. These charts clearly show the reduction in NH_3 concentrations that can be expected when an increased supply temperature is used. A few of the cases do not show significant improvements. These are cases where the original run is already at the minimum RH (61 percent) used in the generation rate calculation.

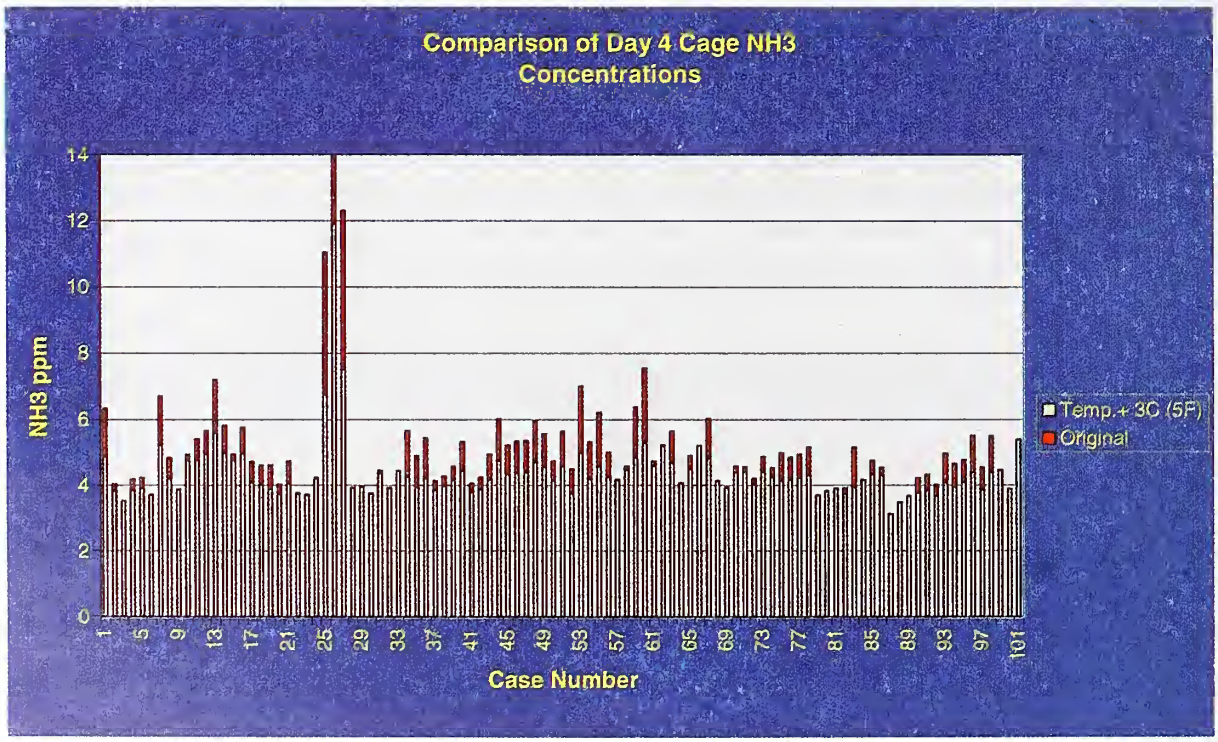


Figure 3.60 Comparison of Cage Day 4 NH_3 Concentrations

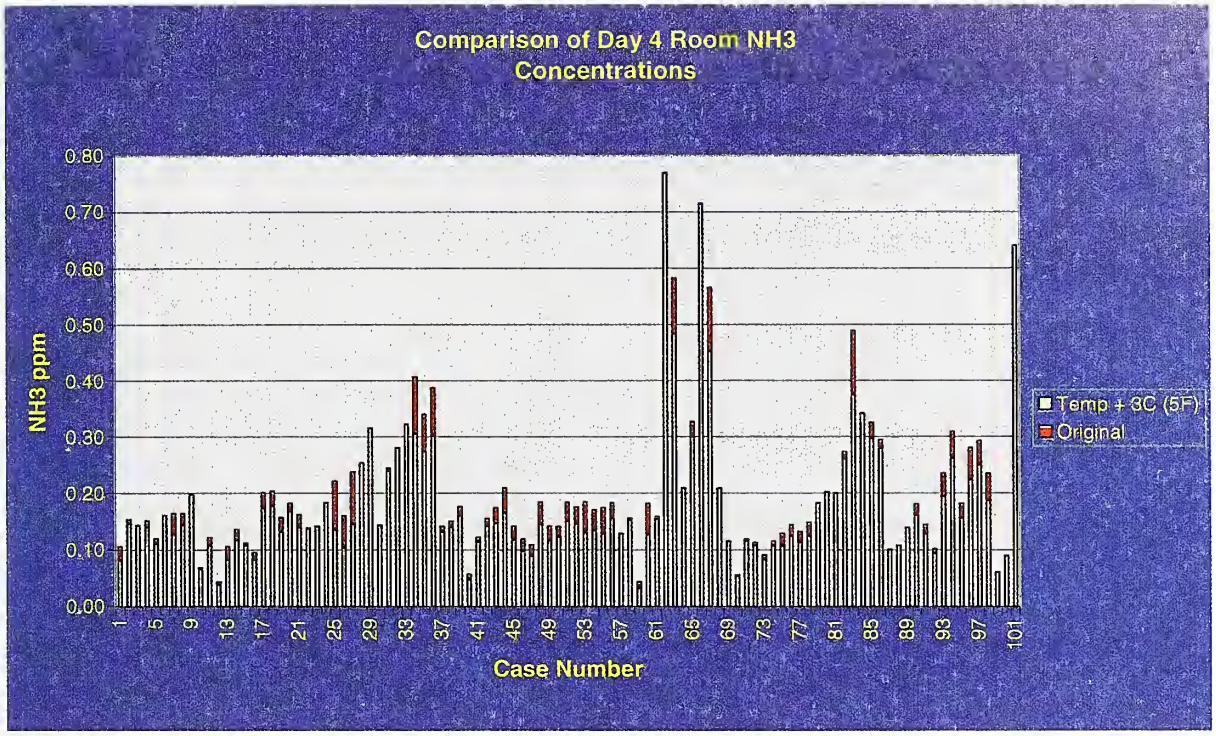


Figure 3.61 *Comparison of Room Day 4 NH_3 Concentrations*

3.2 NH_3 Concentrations for 10-day cycle

Table 3.03 shows a summary of mean and maximum NH_3 concentrations in the room's breathing zone over 10 days using the different generation rates measured in the experiments. In the summary, values between 0.5ppm and 1ppm have been colored blue, and values above 1 ppm are colored red. Smyth (1956) found 1ppm detected and identified by 10 subjects. In addition, analysis of data obtained in plant surveys conducted from 1965 to 1970 by the Bureau of Industrial Hygiene, Detroit Department of Health, found the limit of detection to be below 5 ppm and the complaint level to be 20 ppm to 25 ppm. Therefore, 1ppm was chosen as a conservative level at which people might be able to detect a smell in the room.

With the exception of the very low flow rates (5 ACH) for the double density rooms, all the room configurations show an acceptable NH_3 concentration, on average, in the breathing zone up to day 5. The maximum value in the breathing zone, present in just one small location, is generally all right up to day 5. By day 5 and day 6 virtually all rooms had at least one spot above 1ppm. This indicates that changing the bedding every 5 days should leave most rooms with an acceptable atmosphere.

Table 3.04 shows a summary of mean and maximum NH_3 concentrations in the cages over 10 days using the different generation rates measured in the experiments. In the summary, values over 25 ppm have been colored red, as such high levels are likely to cause problems for the mice.

See Schoeb, Davidson and Lindsey (1982) who indicated that NH_3 concentrations above 25 ppm promote the growth of infective agents in the respiratory tract of rats in cages.

In cases 25-27, in which sealed edge cages with particularly poor ventilation are used (the only airflow is through the filter), the mean concentration did not rise above 25 ppm until day 7 for any of the rooms studied. The "maximum" part of the table shows that the worst cage in the room did go over 25 ppm on day 6 (see cases 73, 75, 77 and 78). By day 7 most rooms have at least one cage with NH_3 concentrations over 25 ppm.

As indicated previously, a supply rate of 0.85 cfm (4.01e-4 m^3/s) per 100g mouse body weight will provide good room conditions up to day 4 or day 5. To go beyond this time before changing the bedding the flow rate must be increased to 1.28 cfm (6.04e-4 m^3/s) per 100g, although a few rooms will be 1 ppm, on average, by day 7. Even increasing to 1.70 cfm (8.02e-4 m^3/s) per 100g will only extend this to eight days, although even then the maximum NH_3 concentration in the breathing zone will rise to 3 ppm and some parts of the room will be noticeably smelly.

Even at 1.70 cfm (8.02e-4 m^3/s) per 100g (20 ACH in the double density rooms) the cages are unacceptable by day 8 as the NH_3 concentration is around 25ppm. The very small amount of improvement that 20 ACH gives over 15 ACH for the cages makes it unlikely that further increases in supply flow rates will change this situation.

Tables 3.05 and 3.06 are repeats of 3.03 and 3.04 with the cage temperatures increased by 3.0 °C (5.4 °F). The increase in temperature reduces the relative humidity as well as the NH_3 generation rate leading to lower NH_3 concentrations.

Increasing the temperature is also recommended by Gordon, Becker and Ali (1997) who indicate that the "standard housing temperature of 22.0-24.0 °C (72.0-75.0 °F) is significantly below the thermoneutral zone of groups of mice suggesting that they are subjected to varying degrees of cold stress under standard housing conditions."

The increase in temperature shows the rooms improve in approximately one day. Considering the average NH_3 concentration, the rooms are acceptable up to day 7 apart from the very low flow rates that fail on day 6. The maximum NH_3 concentration shows an improvement with many more rooms acceptable on day 5 with most starting to fail on day 6.

The cages show nearly a two day improvement with the average cage going over 25 ppm on day 10, although the worst cages with the maximum NH_3 concentration start to fail in a few rooms on day 8, with most failing on day 9.

Note on use of tables 3.03 to 3.06:
The tables show mean NH_3 concentrations for the cages and scientist's breathing zone (1.5m-1.8m, 4'11" – 5' 11") and the maximum value (in one cage or one spot in the room breathing zone). The color coding allows both good (black) and poor (red) cases to be quickly identified. It

is also possible to see how quickly the NH_3 concentrations deteriorate over the 10-day cycle for the particular case.

	Dey by day room breathing zone everage NH3										Dey by dey room breathing zone maximum NH3									
Case Name	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
Basecase	0.02	0.04	0.06	0.11	0.18	0.26	0.40	0.49	0.59	0.63	0.07	0.14	0.21	0.40	0.68	1.01	1.51	1.88	2.25	2.43
Case 02	0.03	0.07	0.10	0.15	0.23	0.32	0.45	0.59	0.76	0.95	0.09	0.18	0.28	0.43	0.63	0.88	1.24	1.64	2.12	2.65
Case 03	0.03	0.06	0.10	0.14	0.20	0.28	0.38	0.52	0.69	0.90	0.09	0.17	0.27	0.38	0.54	0.75	1.02	1.38	1.83	2.39
Case 04	0.03	0.06	0.10	0.15	0.23	0.32	0.46	0.50	0.77	0.94	0.09	0.17	0.26	0.42	0.62	0.89	1.27	1.65	2.10	2.56
Case 05	0.03	0.05	0.08	0.12	0.18	0.25	0.36	0.47	0.60	0.74	0.08	0.16	0.24	0.37	0.56	0.79	1.12	1.47	1.88	2.30
Case 06	0.04	0.07	0.11	0.16	0.23	0.31	0.43	0.58	0.77	1.01	0.08	0.16	0.25	0.35	0.50	0.69	0.94	1.27	1.69	2.21
Case 07	0.03	0.06	0.09	0.16	0.27	0.41	0.61	0.76	0.91	0.99	0.20	0.38	0.58	1.07	1.79	2.65	3.97	4.94	5.94	6.46
Case 08	0.03	0.06	0.10	0.16	0.26	0.37	0.54	0.69	0.86	1.01	0.12	0.23	0.35	0.58	0.91	1.31	1.90	2.43	3.04	3.56
Case 09	0.05	0.09	0.14	0.20	0.28	0.38	0.53	0.71	0.94	1.23	0.14	0.28	0.43	0.62	0.88	1.21	1.66	2.24	2.98	3.89
Case 10	0.02	0.03	0.05	0.07	0.10	0.14	0.19	0.26	0.33	0.42	0.08	0.16	0.25	0.37	0.53	0.75	1.05	1.39	1.81	2.29
Case 11	0.03	0.05	0.07	0.12	0.19	0.27	0.39	0.51	0.63	0.75	0.12	0.23	0.35	0.57	0.88	1.27	1.84	2.36	2.96	3.49
Case 12	0.01	0.02	0.03	0.04	0.07	0.10	0.14	0.18	0.23	0.27	0.12	0.23	0.36	0.59	0.92	1.32	1.92	2.46	3.08	3.63
Case 13	0.02	0.04	0.06	0.11	0.18	0.26	0.39	0.49	0.59	0.84	0.15	0.28	0.44	0.81	1.36	2.01	3.02	3.75	4.51	4.90
Case 14	0.03	0.05	0.08	0.14	0.21	0.31	0.45	0.58	0.72	0.83	0.12	0.22	0.34	0.58	0.91	1.32	1.93	2.45	3.04	3.52
Case 15	0.03	0.05	0.07	0.11	0.16	0.23	0.32	0.42	0.55	0.70	0.16	0.31	0.48	0.71	1.03	1.45	2.02	2.69	3.50	4.43
Case 16	0.02	0.04	0.06	0.10	0.15	0.22	0.31	0.40	0.50	0.58	0.13	0.25	0.39	0.65	1.02	1.48	2.16	2.76	3.43	4.00
Case 17	0.04	0.08	0.12	0.20	0.32	0.46	0.66	0.85	1.06	1.23	0.10	0.18	0.28	0.47	0.73	1.06	1.54	1.97	2.46	2.87
Case 18	0.04	0.08	0.12	0.20	0.32	0.46	0.67	0.85	1.06	1.25	0.10	0.18	0.28	0.47	0.73	1.05	1.53	1.96	2.44	2.86
Case 19	0.03	0.06	0.09	0.16	0.25	0.36	0.54	0.88	0.84	0.96	0.12	0.22	0.35	0.59	0.95	1.38	2.03	2.57	3.16	3.62
Case 20	0.04	0.08	0.12	0.18	0.27	0.39	0.55	0.72	0.92	1.13	0.09	0.18	0.27	0.43	0.64	0.91	1.29	1.68	2.15	2.62
Case 21	0.03	0.06	0.10	0.16	0.26	0.37	0.54	0.59	0.85	0.99	0.10	0.19	0.29	0.49	0.77	1.11	1.62	2.06	2.56	2.98
Case 22	0.03	0.06	0.10	0.14	0.20	0.27	0.37	0.50	0.66	0.86	0.11	0.22	0.34	0.49	0.69	0.97	1.33	1.78	2.36	3.06
Case 23	0.03	0.08	0.10	0.14	0.20	0.28	0.38	0.51	0.68	0.89	0.09	0.18	0.28	0.41	0.57	0.79	1.08	1.46	1.94	2.54
Cese 24	0.04	0.08	0.13	0.18	0.26	0.36	0.49	0.66	0.88	1.15	0.22	0.43	0.67	0.96	1.35	1.87	2.56	3.46	4.59	6.00
Case 25	0.03	0.06	0.09	0.22	0.41	0.63	0.99	1.19	1.36	1.30	0.13	0.24	0.36	0.86	1.60	2.45	3.83	4.59	5.23	5.01
Case 26	0.02	0.04	0.05	0.16	0.32	0.51	0.81	0.95	1.05	0.92	0.08	0.15	0.23	0.69	1.39	2.18	3.50	4.10	4.52	3.96
Case 27	0.03	0.06	0.10	0.24	0.45	0.70	1.10	1.31	1.48	1.39	0.13	0.24	0.37	0.93	1.77	2.72	4.29	5.11	5.77	5.40
Case 28	0.06	0.11	0.18	0.25	0.36	0.50	0.68	0.92	1.22	1.59	0.16	0.31	0.48	0.69	0.97	1.35	1.84	2.48	3.30	4.31
Case 29	0.07	0.14	0.22	0.32	0.44	0.62	0.84	1.14	1.51	1.97	0.14	0.27	0.42	0.60	0.85	1.17	1.60	2.16	2.88	3.76
Case 30	0.03	0.06	0.10	0.14	0.20	0.28	0.38	0.52	0.68	0.89	0.13	0.25	0.39	0.57	0.80	1.10	1.51	2.04	2.71	3.54
Case 31	0.06	0.11	0.17	0.24	0.35	0.49	0.68	0.90	1.19	1.52	0.16	0.32	0.49	0.72	1.04	1.45	2.00	2.68	3.51	4.51
Case 32	0.06	0.13	0.19	0.28	0.39	0.55	0.75	1.01	1.34	1.75	0.18	0.34	0.53	0.76	1.07	1.48	2.02	2.73	3.63	4.74
Case 33	0.07	0.14	0.22	0.32	0.45	0.63	0.86	1.16	1.54	2.01	0.22	0.44	0.67	0.97	1.37	1.90	2.60	3.50	4.65	6.08
Case 34	0.07	0.14	0.21	0.41	0.69	1.03	1.55	1.92	2.29	2.44	0.17	0.32	0.50	0.95	1.61	2.40	3.63	4.49	5.35	5.70
Case 35	0.06	0.12	0.19	0.34	0.56	0.82	1.21	1.52	1.85	2.06	0.15	0.29	0.45	0.81	1.32	1.95	2.89	3.63	4.41	4.91
Case 36	0.07	0.14	0.21	0.39	0.65	0.96	1.44	1.79	2.15	2.34	0.16	0.31	0.47	0.88	1.47	2.18	3.26	4.06	4.88	5.30
Case 37	0.03	0.06	0.09	0.14	0.21	0.30	0.42	0.55	0.71	0.87	0.09	0.18	0.28	0.43	0.64	0.90	1.28	1.68	2.15	2.66
Case 38	0.03	0.06	0.10	0.15	0.22	0.32	0.45	0.59	0.75	0.93	0.10	0.20	0.31	0.47	0.70	1.00	1.41	1.85	2.38	2.93
Case 39	0.04	0.07	0.11	0.18	0.27	0.38	0.55	0.71	0.90	1.08	0.13	0.25	0.39	0.62	0.94	1.34	1.91	2.48	3.15	3.80
Case 40	0.01	0.02	0.03	0.06	0.09	0.13	0.20	0.25	0.31	0.35	0.05	0.09	0.13	0.23	0.37	0.54	0.79	1.00	1.23	1.40
Case 41	0.03	0.05	0.08	0.12	0.18	0.26	0.36	0.47	0.61	0.75	0.07	0.14	0.22	0.34	0.50	0.70	0.99	1.30	1.68	2.08
Case 42	0.03	0.06	0.10	0.16	0.23	0.33	0.48	0.62	0.79	0.96	0.10	0.19	0.30	0.47	0.70	1.00	1.43	1.85	2.36	2.87
Case 43	0.03	0.07	0.10	0.17	0.28	0.40	0.59	0.75	0.93	1.06	0.09	0.17	0.26	0.44	0.70	1.01	1.49	1.89	2.33	2.66
Case 44	0.04	0.07	0.11	0.21	0.35	0.51	0.76	0.95	1.15	1.27	0.13	0.24	0.37	0.67	1.11	1.65	2.46	3.07	3.71	4.07
Cese 45	0.03	0.05	0.08	0.14	0.23	0.33	0.49	0.62	0.78	0.86	0.13	0.25	0.38	0.67	1.07	1.56	2.30	2.91	3.57	4.05
Case 46	0.02	0.04	0.07	0.12	0.19	0.28	0.42	0.53	0.64	0.72	0.11	0.20	0.31	0.55	0.89	1.31	1.94	2.44	2.98	3.34
Case 47	0.02	0.04	0.06	0.11	0.18	0.26	0.38	0.48	0.58	0.66	0.09	0.18	0.27	0.48	0.78	1.14	1.68	2.12	2.59	2.92
Case 48	0.03	0.07	0.10	0.18	0.30	0.45	0.67	0.84	1.01	1.11	0.16	0.31	0.47	0.86	1.42	2.10	3.14	3.92	4.73	5.19
Case 49	0.03	0.05	0.08	0.14	0.23	0.34	0.50	0.63	0.77	0.86	0.13	0.25	0.38	0.68	1.10	1.61	2.38	3.00	3.66	4.11
Case 50	0.03	0.06	0.09	0.14	0.22	0.32	0.46	0.59	0.74	0.86	0.10	0.20	0.31	0.51	0.79	1.14	1.65	2.12	2.65	3.11
Case 51	0.04	0.07	0.10	0.18	0.30	0.44	0.65	0.82	1.00	1.12	0.12	0.23	0.36	0.63	1.03	1.51	2.23	2.81	3.42	3.83
Case 52	0.03	0.07	0.10	0.18	0.28	0.41	0.60	0.76	0.94	1.07	0.19	0.37	0.57	0.98	1.57	2.29	3.37	4.26	5.24	5.95
Case 53	0.03	0.06	0.09	0.18	0.32	0.49	0.74	0.91	1.07	1.10	0.09	0.17	0.26	0.53	0.93	1.40	2.14	2.62	3.08	3.18
Case 54	0.03	0.06	0.09	0.17	0.28	0.42	0.82	0.78	0.94	1.03	0.15	0.29	0.44	0.81	1.33	1.97	2.94	3.67	4.43	4.87
Case 55	0.03	0.06	0.09	0.17	0.30	0.45	0.68	0.84	0.99	1.04	0.13	0.24	0.38	0.74	1.26	1.89	2.86	3.53	4.18	4.40
Case 56	0.04	0.07	0.11	0.18	0.29	0.42	0.62	0.79	0.98	1.12	0.08	0.16	0.25	0.42	0.66	0.96	1.41	1.79	2.21	2.54
Case 57	0.03	0.06	0.09	0.13	0.18	0.25	0.34	0.46	0.62	0.81	0.15	0.28	0.44	0.63	0.88	1.22	1.68	2.26	3.00	3.92
Case 58	0.04	0.07	0.11	0.16	0.22	0.31	0.43	0.58	0.76	0.97	0.13	0.26	0.40	0.58	0.84	1.17	1.62	2.16	2.83	3.63
Case 59	0.01	0.01	0.02	0.04	0.07	0.11	0.16	0.20	0.24	0.26	0.05	0.09	0.14	0.27	0.45	0.67	1.01	1.25	1.49	1.60
Case 60	0.03	0.06	0.09	0.18	0.32	0.48	0.74	0.90	1.05	1.08	0.09	0.18	0.27	0.56	0.99	1.48	2.27	2.77	3.25	3.33
Case 61	0.04	0.07	0.11	0.16	0.23	0.32	0.45	0.59	0.78	0.99	0.16	0.31	0.48	0.72	1.03	1.45	2.01	2.68	3.50	4.47
Case 62	0.18	0.35	0.53	0.77	1.08	1.50	2.05	2.77	3.68	4.81	0.47	0.91	1.40	2.02	2.84	3.94	5.39	7.27	9.65	12.61
Case 63	0.11	0.22	0.34	0.58	0.94	1.37	2.02	2.55	3.13	3.54	0.34	0.66	1.01	1.76	2.83	4.14	6.10	7.71	9.46	10.71
Case 64	0.05	0.09	0.15	0.21	0.29	0.41	0.56	0.75	1.00	1.31	0.17	0.33	0.51	0.73	1.02	1.42	1.94	2.62	3.48	4.55
Case 65	0.07	0.14	0.21	0.33	0.49	0.70	0.99	1.30	1.65	2.01	0.17	0.32	0.50	0.79	1.18	1.68	2.39	3.12	3.97	4.85
Case 66	0.17	0.32	0.50	0.72	1.01	1.40	1.91	2.58	3.42	4.47	0.43	0.83	1.28	1.84	2.59	3.59	4.91	6.63	8.81	11.51
Case 67	0.11	0.20	0.31	0.57	0.93	1.37	2.04	2.55	3.10	3.42	0.33	0.63	0.97	1.75	2.88	4.26	6.32	7.92	9.60	10.61
Case 68	0.05	0.09	0.15	0.21	0.29	0.41	0.56	0.75	1.00	1.31	0.14	0.26	0.41	0.59	0.83	1.15	1.57	2.12	2.81	3.68
Case 69	0.03	0.05	0.08	0.12	0.16	0.22	0.31	0.41	0.55	0.72	0.14	0.28	0.41	0.59	0.82	1.14	1.56	2.11	2.80	3.66
Case 70	0.01	0.02	0.04	0.06	0.08	0.11	0.16	0.21	0.28	0.35	0.06	0.12	0.19	0.29	0.42	0.58	0.82	1.08	1.41	1.78
Case 71	0.03	0.05	0.08	0.12	0.17	0.24	0.34	0.45	0.58	0.74	0.16	0.31	0.48	0.71	1.02	1.43	1.99	2.65	3.46	4.40
Case 72	0.03	0.05	0.07	0.11	0.17	0.23	0.33	0.43	0.56	0.70	0.13	0.26	0.40	0.60	0.87	1.23	1.72	2.27	2.95	3.70
Case 73	0.02	0.04	0.06	0.09	0.14	0.20	0.28	0.37	0.47	0.56	0.08	0.15	0.23	0.36	0.55	0.78	1.12	1.45	1.84	2.22
Case 74	0.02	0.05	0.07	0.11	0.17	0.24	0.34	0.45	0.57	0.71	0.13	0.25	0.39	0.59	0.88	1.25	1.77	2.32	2.98	3.68
Case 75	0.03	0.05	0.07	0.13	0.21	0.30	0.45	0.57	0.69	0.79	0.13	0.25	0.39	0.67	1.08	1.57	2.32	2.93	3.60	4.07
Case 76	0.03	0.06	0.09	0.14	0.23	0.33	0.48	0.61	0.78	0.88	0.12	0.24	0.37	0.62	0.97	1.40	2.04	2.61	3.24	3.77
Case 77	0.03	0.05	0.08	0.13	0.21	0.30	0.44	0.56	0.70	0.81	0.10	0.19	0.30	0.50	0.79	1.14	1.67	2.13	2.64	3.06
Case 78	0.03	0.06	0.09	0.15	0.24	0.35	0.51	0.64	0.79	0.90	0.11	0.21	0.33	0.57	0.91	1.33	1.95	2.47	3.04	3.46
Case 79	0.04	0.08	0.13	0.18	0.26	0.36	0.49	0.66	0.87	1.14	0.10	0.20	0.30	0.44	0.62	0.86	1.17	1.58	2.10	2.74
Case 80	0.05	0.09	0.14	0.20	0.29	0.40	0.54	0.73	0.97	1.27	0.11	0.21	0.32	0.47	0.65	0.91	1.24	1.68	2.23	2.91
Cese 81	0.05	0.09	0.14	0.20	0.28	0.39	0.54	0.72	0.96	1.25	0.14	0.28	0.43	0.63	0.88	1.22	1.67	2.25	2.99	3.91
Case 82	0.06	0.12	0.18	0.27	0.40	0.56	0.79	1.04	1.35	1.70	0.17	0.34	0.52	0.78	1.14	1.61	2.25	2.97	3.86	4.86
Cese 83	0.09	0.17	0.28	0.49	0.82	1.22	1.84	2.28	2.73	2.94	0.21	0.41	0.63	1.18	1.99	2.95	4.44	5.51	6.60	7.11
Case 84	0.08	0.15	0.24	0.34	0.48	0.67	0.91	1.23	1.64	2.14	0.20	0.38	0.59	0.85	1.20	1.67	2.28	3.07	4.08	5.34
Case 85	0.07	0.13	0.21	0.33	0.49	0.70	1.00	1.30	1.65	2.00	0.23	0.45	0.69	1.10	1.66	2.36	3.37	4.38	5.57	6.75
Case 86	0.06	0.13	0.19	0.29	0.43	0.61	0.85	1.13	1.46	1.82	0.20	0.38	0.58	0.89	1.30	1.83	2.57	3.39	4.39	5.49
Case 87	0.02	0.05	0.07	0.10	0.14	0.20	0.27	0.36	0.48	0.63	0.07	0.14	0.21	0.30	0.42	0.59	0.81	1.09	1.44	1.89
Case 88	0.02	0.05	0.07	0.11	0.15	0.21	0.29	0.39	0.51	0.67	0.04	0.09	0.13	0.19	0.27	0.38	0.51	0.69	0.92	1.21
Case 89	0.03	0.06	0.10	0.14	0.20	0.27	0.37	0.50	0.67	0.87	0.11	0.22	0.34	0.49	0.69	0.95	1.30	1.75	2.33	3.04
Case 90	0.04	0.07	0.11	0.18	0.28	0.40	0.57	0.74	0.93	1.11	0.15	0.28	0.44	0.70	1.08	1.55	2.24	2.89	3.63	4.33
Case 91	0.03	0.06	0.09	0.14	0.22	0.32	0.46	0.59	0.75	0.89	0.10	0.19	0.29	0.46	0.71	1.03	1.48	1.90	2.39	2.85
Case 92	0.02	0.04	0.06	0.10	0.15	0.22	0.31	0.41	0.52	0.63	0.08	0.15	0.24	0.37	0.56	0.80	1.14	1.48	1.88	2.29
Case 93	0.05	0.09	0.13	0.24	0.38	0.56	0.82	1.04	1.27	1.43	0.19	0.37	0.56	0.98	1.59	2.33	3.43	4.33	5.30	5.98
Case 94	0.06	0.12	0.18	0.31	0.49	0.71	1.04	1.33	1.64	1.89	0.17	0.33	0.51	0.87	1.38	2.01	2.94	3.73	4.61	5.31
Case 95	0.04	0.07	0.11	0.18	0.29	0.41	0.60	0.77	0.96	1.11	0.15	0.28	0.44	0.74	1.16	1.68	2.44	3.12	3.87	4.49
Case 96	0.05	0.10	0.16	0.28	0.46	0.68	1.01	1.27	1.54	1.70	0.15	0.28	0.44	0.79	1.30	1.91	2.85	3.56	4.32	4.77
Case 97	0.06	0.11	0.17	0.29	0.46	0.67	0.98	1.25	1.54	1.79	0.15	0.30	0.46	0.77	1.22	1.77	2.59	3.29	4.08	4.72
Case 98	0.04	0.08	0.13	0.23	0.39	0.57	0.85	1.06	1.29	1.42	0.18	0.34	0.52	0.94	1.54	2.28	3.39	4.24	5.14	5.68
Case 99	0.01	0.03	0.04	0.08	0.09	0.12	0.16	0.22	0.29	0.38	0.06	0.12	0.19	0.28	0.39	0.54	0.74	1.00	1.33	1.73
Case 100	0.02	0.04	0.06	0.09	0.13	0.18	0.24	0.32	0.43	0.56	0.10	0.19	0.30	0.43	0.61	0.84	1.16	1.56	2.07	2.71
Case 101	0.15	0.29	0.44	0.64	0.90	1.25	1.71	2.30	3.06	4.00	0.41	0.80	1.24	1.78	2.51	3.48	4.76	6.42	8.53	11.15

Table 3.03 Room Breathing Zone NH_3 Mean and Maximum Concentrations for 10 Days

	Day by day cage average NH3										Day by day cage maximum NH3									
Case Name	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
Basecase	1.15	2.18	3.37	6.33	10.66	15.82	23.78	29.51	35.35	38.09	1.67	3.17	4.89	9.19	15.47	22.86	34.53	42.64	51.32	55.30
Case 02	0.89	1.72	2.66	4.03	5.92	8.35	11.72	15.45	19.99	25.01	1.29	2.51	3.87	5.87	8.61	12.14	17.05	22.48	29.08	36.39
Case 03	0.82	1.59	2.45	3.53	4.96	6.88	9.41	12.70	16.87	22.05	1.34	2.61	4.03	5.81	8.16	11.32	15.50	20.90	27.76	36.29
Case 04	0.90	1.73	2.67	4.18	6.29	8.96	12.76	16.61	21.17	25.80	1.20	2.32	3.58	5.62	8.45	12.03	17.13	22.31	28.44	34.67
Case 05	0.91	1.76	2.72	4.23	6.32	8.99	12.75	16.66	21.31	26.14	1.22	2.36	3.64	5.67	8.46	12.03	17.07	22.30	28.53	34.99
Case 06	0.86	1.67	2.58	3.72	5.22	7.24	9.92	13.37	17.76	23.22	1.38	2.68	4.13	5.95	8.37	11.60	15.88	21.42	28.44	37.18
Case 07	1.24	2.35	3.62	6.71	11.21	16.60	24.87	30.95	37.22	40.46	1.80	3.43	5.28	9.79	16.35	24.20	36.26	45.13	54.28	59.00
Case 08	0.98	1.89	2.92	4.83	7.53	10.88	15.79	20.22	25.23	29.56	1.39	2.67	4.12	6.81	10.62	15.34	22.26	28.50	35.57	41.68
Case 09	0.90	1.75	2.69	3.88	5.46	7.57	10.36	13.97	18.55	24.26	1.52	2.97	4.57	6.59	9.27	12.86	17.60	23.74	31.53	41.21
Case 10	1.11	2.14	3.31	4.94	7.17	10.06	14.03	18.61	24.25	30.72	1.67	3.24	5.00	7.47	10.83	15.20	21.20	28.12	36.65	46.42
Case 11	1.11	2.14	3.30	5.42	8.40	12.10	17.51	22.48	28.16	33.21	1.53	2.84	4.53	7.43	11.61	16.59	24.01	30.82	38.60	45.52
Case 12	1.16	2.23	3.45	5.88	8.78	12.66	18.32	23.52	29.43	34.67	1.59	3.06	4.72	7.75	12.02	17.33	25.09	32.20	40.30	47.47
Case 13	1.33	2.52	3.89	7.21	12.05	17.85	26.75	33.29	40.02	43.47	1.60	3.04	4.68	8.69	14.52	21.50	32.23	40.10	48.21	52.37
Case 14	1.17	2.24	3.46	6.82	9.17	13.30	19.40	24.73	30.67	35.51	1.38	2.65	4.09	6.88	10.84	15.72	22.94	29.23	36.26	41.99
Case 15	1.11	2.14	3.31	4.94	7.17	10.08	14.03	18.61	24.25	30.72	1.67	3.24	5.00	7.47	10.83	15.20	21.20	28.12	36.65	46.42
Case 16	1.17	2.24	3.45	5.76	9.02	13.05	18.99	24.28	30.19	35.20	1.65	3.16	4.88	8.13	12.74	18.43	26.82	34.26	42.65	49.71
Case 17	0.96	1.84	2.83	4.71	7.38	10.67	15.52	19.84	24.70	28.82	1.30	2.49	3.84	6.40	10.01	14.49	21.07	26.93	33.54	39.13
Case 18	0.94	1.81	2.79	4.62	7.19	10.39	15.07	19.30	24.10	28.27	1.28	2.47	3.80	6.28	9.78	14.12	20.48	26.24	32.77	38.44
Case 19	0.91	1.75	2.69	4.61	7.36	10.72	15.74	19.95	24.59	28.11	1.24	2.38	3.67	6.29	10.04	14.63	21.46	27.21	33.53	38.34
Case 20	0.87	1.68	2.58	4.04	6.06	8.62	12.26	15.98	20.40	24.94	1.23	2.38	3.67	5.74	8.60	12.25	17.41	22.70	28.98	35.42
Case 21	0.85	1.83	2.82	4.73	7.44	10.79	15.72	20.05	24.90	28.90	1.35	2.59	3.89	6.69	10.52	15.24	22.22	28.34	35.20	40.85
Case 22	0.87	1.69	2.60	3.77	5.34	7.42	10.20	13.71	18.13	23.55	1.37	2.66	4.09	5.94	8.41	11.69	16.06	21.59	28.57	37.11
Case 23	0.86	1.67	2.58	3.71	6.22	7.24	9.91	13.37	17.76	23.22	1.33	2.58	3.88	5.74	8.07	11.19	15.32	20.67	27.45	35.88
Case 24	0.98	1.91	2.94	4.24	5.96	8.26	11.30	15.25	20.25	26.47	1.57	3.08	4.72	6.80	9.56	13.26	18.14	24.47	32.50	42.49
Case 25	1.64	3.04	4.69	11.05	20.64	31.63	49.49	59.31	67.59	64.80	2.15	3.99	6.15	14.47	27.02	41.42	64.81	77.66	88.51	84.85
Case 26	2.26	4.02	6.20	18.42	37.17	58.21	93.38	109.47	120.68	105.66	2.73	4.90	7.55	22.42	45.23	70.83	113.63	133.21	146.85	128.57
Case 27	1.75	3.21	4.95	12.31	23.47	36.19	57.03	67.91	76.69	71.78	2.51	4.81	7.11	17.70	33.74	52.03	81.98	97.63	110.26	103.19
Case 28	0.91	1.77	2.73	3.93	5.63	7.67	10.50	14.16	18.81	24.59	1.41	2.74	4.22	6.08	8.56	11.86	16.24	21.90	29.09	38.02
Case 29	0.92	1.79	2.75	3.97	5.58	7.74	10.59	14.28	18.97	24.80	1.33	2.59	3.99	5.75	8.08	11.21	15.34	20.70	27.49	35.93
Case 30	0.87	1.69	2.80	3.75	5.27	7.31	10.01	13.50	17.93	23.44	1.34	2.61	4.02	5.79	8.15	11.30	15.47	20.86	27.71	36.22
Case 31	1.01	1.96	3.02	4.45	6.37	8.89	12.30	16.44	21.59	27.73	1.48	2.87	4.43	6.52	9.33	13.03	18.02	24.08	31.63	40.61
Case 32	0.91	1.77	2.73	3.93	6.53	7.66	10.49	14.15	18.79	24.57	1.45	2.82	4.35	6.27	8.82	12.23	16.74	22.59	30.00	39.21
Case 33	1.03	2.00	3.08	4.44	6.24	8.66	11.85	15.98	21.23	27.75	1.63	3.17	4.89	7.05	9.91	13.74	18.81	25.37	33.69	44.04
Case 34	1.01	1.92	2.86	5.66	9.63	14.34	21.65	26.77	31.90	34.00	1.44	2.72	4.20	8.03	13.66	20.34	30.71	37.96	45.24	48.23
Case 35	0.93	1.78	2.75	4.90	8.01	11.77	17.46	21.92	26.67	29.69	1.43	2.72	4.20	7.49	12.24	17.99	26.70	33.51	40.76	45.38
Case 36	1.00	1.80	2.93	5.44	9.09	13.47	20.19	25.12	30.19	32.78	1.38	2.83	4.05	7.51	12.56	18.60	27.88	34.69	41.70	45.28
Case 37	0.90	1.74	2.68	4.13	6.14	8.70	12.31	16.12	20.70	25.55	1.17	2.27	3.50	5.41	8.03	11.38	16.10	21.09	27.08	33.42
Case 38	0.93	1.80	2.77	4.28	6.36	9.02	12.75	16.71	21.45	26.46	1.39	2.70	4.16	6.42	8.54	13.54	18.15	25.08	32.19	39.73
Case 39	0.97	1.87	2.88	4.58	6.94	9.92	14.18	18.39	23.33	28.19	1.41	2.72	4.19	6.65	10.08	14.40	20.59	26.72	33.89	40.94
Case 40	1.04	2.00	3.08	5.33	8.55	12.48	18.36	23.22	28.53	32.42	1.47	2.81	4.34	7.50	12.02	17.55	25.82	32.66	40.12	45.60
Case 41	0.88	1.71	2.64	4.06	6.01	8.51	12.02	15.77	20.28	25.10	1.25	2.41	3.71	5.72	8.47	11.99	16.93	22.21	28.56	35.36
Case 42	0.91	1.75	2.70	4.25	6.41	9.14	13.03	16.94	21.56	26.19	1.33	2.57	3.96	6.23	9.40	13.40	19.11	24.86	31.63	38.42
Case 43	0.98	1.88	2.90	4.96	7.90	11.50	16.87	21.40	26.38	30.19	1.28	2.46	3.79	8.49	10.34	15.06	22.09	28.02	34.54	39.52
Case 44	1.13	2.14	3.31	8.03	9.97	14.71	21.96	27.43	33.15	36.40	1.45	2.77	4.26	7.77	12.86	18.98	28.33	35.38	42.75	46.95
Case 45	1.02	1.86	3.01	5.22	8.40	12.27	18.08	22.84	28.03	31.77	1.42	2.71	4.18	7.26	11.68	17.06	25.13	31.76	38.96	44.16
Case 46	1.03	1.97	3.03	5.35	8.68	12.72	18.82	23.69	28.92	32.44	1.45	2.78	4.28	7.56	12.26	17.97	26.60	33.48	40.87	45.84
Case 47	1.04	1.98	3.06	5.36	8.67	12.68	18.73	23.62	28.89	32.55	1.48	2.84	4.38	7.67	12.40	18.15	26.80	33.79	41.34	46.57
Case 48	1.12	2.12	3.28	5.98	9.91	14.62	21.83	27.26	32.92	36.12	1.44	2.75	4.24	7.73	12.81	18.91	28.23	35.25	42.58	46.71
Case 49	1.07	2.05	3.16	5.66	9.02	13.21	19.54	24.61	30.06	33.76	1.42	2.72	4.19	7.37	11.95	17.51	25.89	32.60	39.82	44.72
Case 50	0.97	1.86	2.87	4.73	7.36	10.62	15.40	19.74	24.67	28.99	1.36	2.63	4.05	6.67	10.37	14.97	21.70	27.81	34.76	40.85
Case 51	1.08	2.07	3.19	5.64	9.17	13.45	19.91	25.05	30.56	34.22	1.44	2.74	4.23	7.48	12.15	17.82	26.39	33.19	40.49	45.34
Case 52	0.88	1.69	2.60	4.49	7.20	10.51	15.47	19.57	24.04	27.33	1.39	2.66	4.09	7.08	11.35	16.56	24.37	30.83	37.88	43.05
Case 53	1.19	2.24	3.45	7.02	12.29	18.48	28.24	34.54	40.56	41.81	1.52	2.86	4.41	8.96	15.70	23.61	36.08	44.13	51.82	53.41
Case 54	0.99	1.89	2.92	6.32	8.80	12.98	19.37	24.20	29.24	32.12	1.42	2.71	4.18	7.61	12.60	18.59	27.75	34.66	41.88	46.00
Case 55	1.09	2.06	3.18	6.22	10.69	15.97	24.22	29.83	35.36	37.24	1.40	2.66	4.09	8.00	13.75	20.55	31.16	38.38	45.49	47.92
Case 56	1.00	1.91	2.94	6.01	7.95	11.56	16.93	21.50	26.57	30.53	1.36	2.60	4.01	6.82	10.84	15.76	23.07	29.31	36.21	41.61
Case 57	0.96	1.88	2.89	4.17	5.87	8.14	11.13	15.02	19.95	26.08	1.43	2.77	4.28	8.17	8.67	12.02	16.46	22.20	29.48	38.54
Case 58	1.04	2.01	3.10	4.58	6.56	9.16	12.68	16.93	22.23	28.50	1.50	2.90	4.48	6.60	9.45	13.21	18.29	24.42	32.05	41.10
Case 59	1.15	2.19	3.37	6.38	10.78	16.02	24.13	29.90	35.75	38.37	1.46	2.77	4.27	8.09	13.66	20.30	30.57	37.89	45.30	48.62
Case 60	1.27	2.38	3.67	7.56	13.31	20.05	30.71	37.49	43.90	44.97	1.58	2.96	4.57	9.40	16.57	24.95	38.22	46.66	54.63	55.95
Case 61	1.06	2.07	3.19	4.73	6.81	9.54	13.26	17.64	23.08	29.42	1.47	2.86	4.41	6.54	9.42	13.20	18.33	24.40	31.92	40.69
Case 62	1.21	2.35	3.63	5.23	7.36	10.20	13.98	18.83	25.01	32.69	1.76	3.43	5.29	7.62	10.72	14.86	20.34	27.44	36.44	47.64
Case 63	1.10	2.11	3.25	5.64	9.08	13.26	19.55	24.69	30.29	34.30	1.80	3.44	5.31	9.23	14.84	21.69	31.96	40.37	49.52	56.09
Case 64	0.94	1.83	2.82	4.07	5.72	7.93	10.85	14.64	19.44	25.42	1.36	2.65	4.09	5.89	8.28	11.48	15.71	21.20	28.15	36.80
Case 65	1.05	2.03	3.12	4.90	7.36	10.48	14.92	19.44	24.79	30.23	1.65	3.19	4.91	7.70	11.57	16.49	23.46	30.57	38.97	47.53
Case 66	1.21	2.35	3.62	5.21	7.33	10.17	13.91	18.77	24.92	32.58	1.80	3.51	5.41	7.80	10.97	15.21	20.82	28.08	37.30	48.76
Case 67	1.14	2.17	3.34	6.03	9.92	14.61	21.75	27.23	33.01	36.49	1.81	3.45	5.31	9.58	15.76	23.20	34.53	43.24	52.41	57.95
Case 68	0.96	1.86	2.87	4.13	5.81	8.06	11.03	14.89	19.77	25.84	1.51	2.93	4.52	6.52	9.17	12.71	17.40	23.47	31.17	40.75
Case 69	0.91	1.77	2.73	3.94	5.54	7.68	10.51	14.17	18.82	24.61	1.34	2.61	4.03	5.81	8.17	11.33	15.50	20.91	27.77	36.30
Case 70	1.02	1.98	3.05	4.68	6.66	9.36	13.08	17.32	22.53	28.44	1.43	2.77	4.28	6.42	9.33	13.12	18.33	24.28	31.58	39.88
Case 71	1.03	1.99	3.07	4.56	6.58	9.22	12.82	17.06	22.30	28.39	1.40	2.72	4.19	6.22	8.97	12.58	17.48	23.26	30.40	38.70
Case 72	0.93	1.81	2.79	4.22	6.15	8.67	12.14	16.04	20.81	26.16	1.39	2.69	4.15	6.27	9.16	12.90	18.06	23.87	30.96	38.92
Case 73	1.03	1.99	3.07	4.87	7.39	10.57	15.12	19.61	24.86	30.01	1.42	2.73	4.22	6.70	10.16	14.53	20.78	26.95	34.17	41.25
Case 74	0.99	1.91	2.94	4.53	6.72	9.53	13.46	17.65	22.68	28.03	1.38	2.66	4.11	6.33	9.39	13.31	18.81	24.66	31.69	39.17
Case 75	0.97	1.86	2.87	4.98	8.01	11.70	17.24	21.79	26.73	30.30	1.39	2.65	4.09	7.10	11.42	16.69	24.58	31.06	38.11	43.20
Case 76	0.98	1.88	2.90	4.85	7.61	11.03	16.07	20.51	25.49	29.63	1.28	2.46	3.80	6.36	9.98	14.48	21.07	26.89	33.42	38.85
Case 77	0.99	1.90	2.93	4.94	7.78	11.29	16.47	20.98	26.03	30.16	1.40	2.68	4.14	6.96	10.97	15.91	23.22	29.59	36.70	42.51
Case 78	1.01	1.94	2.99	5.16	8.25	12.03	17.67	22.38	27.54	31.38	1.39	2.66	4.10	7.05	11.28	16.45	24.17	30.61	37.66	42.92
Case 79	0.86	1.67	2.57	3.70	5.21	7.22	9.88	13.33	17.71	23.15	1.22	2.38	3.67	5.30	7.45	10.33	14.13	19.07	25.32	33.10
Case 80	0.89	1.73	2.66	3.84	5.40	7.49	10.24	13.82	18.35	23.99	1.40	2.72	4.19	6.05	8.50	11.79	16.14	21.77	28.91	37.79
Case 81	0.91	1.76	2.72	3.92	5.51	7.64	10.45	14.10	18.72	24.47	1.41	2.75	4.24	6.12	8.60	11.93	16.33	22.03	29.25	38.24
Case 82	0.87	1.69	2.60	3.92	5.72	8.06	11.28	14.91	19.35	24.34	1.46	2.83	4.36	6.58	9.59	13.51	18.91	25.00	32.45	40.81
Case 83	0.94	1.78	2.74	5.15	8.67	12.87	19.34	24.01	28.75	30.99	1.61	3.06	4.72	8.87	14.92	22.15	33.31	41.33	49.50	53.35
Case 84	0.96	1.88	2.89	4.17	5.86	8.13	11.12	15.00	19.93	26.05	1.54	3.00	4.62	6.67	9.37	13.00	17.79	24.00	31.87	41.66
Case 85	1.01	1.95	3.01	4.76	7.19	10.26	14.64	19.02	24.18	29.32	1.49	2.87	4.43	7.00	10.57	15.09	21.54	27.99	35.58	43.14
Case 86	1.00	1.94	2.99	4.54	6.66	9.39	13.19	17.39	22.60	28.15	1.70	3.29	5.07	7.70	11.28	15.92	22.35	29.47	38.13	47.71
Case 87	0.72	1.41	2.17	3.13	4.40	6.10	8.35	11.26	14.96	19.55	1.37	2.67	4.12	5.93	8.34	11.57	15.84	21.36	28.37	37.09
Case 88	0.81	1.57	2.42	3.49	4.90	6.80	9.30	12.55	16.67	21.78	1.31	2.55	3.93	5.66	7.96	11.04	15.10	20.37	27.06	35.37
Case 89	0.85	1.66	2.55	3.68	5.17	7.17	9.82	13.25	17.59	23.00	1.35	2.63	4.05	5.85	8.22	11.40	15.60	21.04	27.95	36.53
Case 90	0.88	1.69	2.61	4.22	6.48	9.32	13.41	17.29	21.77	25.93	1.32	2.54	3.92	6.34	9.73	13.98	20.13	25.96	32.68	38.92
Case 91	0.90	1.73	2.67	4.33	6.65	9.57	13.79	17.76	22.33	26.55	1.39	2.68	4.12	6.69	10.29	14.79	21.32	27.47	34.54	41.07
Case 92	0.86	1.65	2.55	4.02	6.06	8.65	12.33	16.04	20.39	24.75	1.26	2.43	3.75	5.92	8.93	12.74	18.18	23.63	30.06	36.48
Case 93	0.96	1.84	2.84	4.97	8.02	11.74	17.32	21.85	26.75	30.18	1.47	2.81	4.34	7.58	12.24	17.91	26.44	33.35	40.83	46.07
Case 94	0.93	1.78	2.74	4.66	7.38	10.73	15.71	19.97	24.68	28.40	1.44	2.77	4.27	7.24	11.49	16.70	24.44	31.06	38.40	44.18
Case 95	0.96	1.84	2.84	4.77	7.50	10.87	15.84	20.21	25.09	29.12	1.47	2.81	4.34	7.28	11.44	16.59	24.18	30.84	38.30	44.45
Case 96	1.04	1.98	3.05	5.51	9.06	13.35	19.87	24.88	30.15	33.32	1.47	2.80	4.31	7.78	12.80	18.85	28.06	35.12	42.57	47.05
Case 97	0.91	1.75	2.69	4.54	7.16	10.39	15.18	19.33	23.96	27.70	1.52	2.92	4.50	7.59	11.98	17.39	25.38	32.33	40.07	46.34
Case 98	1.04	1.98	3.05	5.50	9.05	13.33	19.85	24.85	30.12	33.29	1.44	2.74	4.23	7.64	12.56	18.50	27.54	34.46	41.79	46.19
Case 99	1.03	2.01	3.10	4.46	6.28	8.70	11.91	16.07	21.34	27.89	1.54	3.00	4.62	6.66	9.36	12.98	17.76	23.96	31.82	41.60
Cese 100	0.90	1.75	2.70	3.89	5.47	7.59	10.38	14.01	18.61	24.32	1.72	3.35	5.16	7.43	10.46	14.50	19.84	26.77	35.55	46.47
Cese 101	1.25	2.43	3.74	5.40	7.59	10.53	14.40	19.43	25.81	33.74	1.83	3.56	5.50	7.92	11.14	15.45	21.14	28.51	37.87	49.50

Table 3.04 Cage NH_3 Mean and Maximum Concentrations for 10 Days

	Day by day room breathing zone average NH3										Day by day room breathing zone maximum NH3									
Case Name	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
Basecase	0.02	0.04	0.06	0.08	0.11	0.16	0.22	0.29	0.39	0.51	0.07	0.14	0.21	0.31	0.43	0.60	0.83	1.11	1.48	1.93
Case 02	0.03	0.07	0.10	0.15	0.21	0.28	0.39	0.53	0.70	0.91	0.09	0.18	0.28	0.41	0.57	0.79	1.08	1.46	1.94	2.53
Case 03	0.03	0.06	0.10	0.14	0.20	0.28	0.38	0.52	0.69	0.90	0.09	0.17	0.27	0.38	0.54	0.75	1.02	1.38	1.83	2.39
Case 04	0.03	0.06	0.10	0.14	0.20	0.27	0.37	0.50	0.67	0.87	0.09	0.17	0.26	0.38	0.54	0.74	1.02	1.37	1.83	2.39
Case 05	0.03	0.05	0.08	0.11	0.18	0.22	0.30	0.40	0.53	0.69	0.08	0.16	0.24	0.35	0.49	0.67	0.92	1.24	1.65	2.16
Case 06	0.04	0.07	0.11	0.16	0.23	0.31	0.43	0.58	0.77	1.01	0.08	0.16	0.25	0.35	0.50	0.69	0.94	1.27	1.69	2.21
Case 07	0.03	0.06	0.09	0.13	0.18	0.25	0.34	0.46	0.61	0.80	0.19	0.38	0.58	0.83	1.17	1.63	2.23	3.00	3.99	5.21
Case 08	0.03	0.06	0.10	0.14	0.20	0.28	0.38	0.52	0.88	0.89	0.12	0.23	0.35	0.51	0.71	0.99	1.35	1.82	2.42	3.16
Case 09	0.05	0.09	0.14	0.20	0.28	0.38	0.53	0.71	0.94	1.23	0.14	0.28	0.43	0.62	0.88	1.21	1.66	2.24	2.98	3.89
Case 10	0.02	0.03	0.05	0.07	0.09	0.13	0.18	0.24	0.31	0.41	0.08	0.16	0.25	0.36	0.50	0.69	0.95	1.28	1.70	2.22
Case 11	0.02	0.05	0.07	0.11	0.15	0.21	0.29	0.39	0.51	0.67	0.12	0.23	0.35	0.50	0.70	0.98	1.34	1.80	2.39	3.13
Case 12	0.01	0.02	0.03	0.04	0.05	0.07	0.10	0.14	0.18	0.24	0.12	0.23	0.36	0.52	0.73	1.01	1.39	1.87	2.48	3.25
Case 13	0.02	0.04	0.06	0.08	0.12	0.16	0.22	0.30	0.39	0.52	0.15	0.28	0.44	0.63	0.89	1.23	1.69	2.27	3.02	3.95
Case 14	0.03	0.05	0.08	0.12	0.16	0.23	0.31	0.42	0.56	0.73	0.11	0.22	0.34	0.49	0.70	0.96	1.32	1.78	2.36	3.09
Case 15	0.02	0.05	0.07	0.11	0.15	0.21	0.29	0.39	0.52	0.67	0.16	0.31	0.48	0.69	0.97	1.34	1.83	2.48	3.29	4.30
Case 16	0.02	0.04	0.06	0.08	0.12	0.16	0.22	0.30	0.39	0.52	0.13	0.25	0.39	0.57	0.80	1.10	1.51	2.04	2.70	3.53
Case 17	0.04	0.08	0.12	0.17	0.25	0.34	0.47	0.63	0.83	1.09	0.09	0.18	0.28	0.41	0.57	0.79	1.08	1.46	1.94	2.54
Case 18	0.04	0.08	0.12	0.18	0.25	0.35	0.47	0.64	0.85	1.11	0.09	0.18	0.28	0.41	0.57	0.80	1.09	1.47	1.95	2.55
Cese 19	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.48	0.63	0.83	0.12	0.22	0.35	0.50	0.70	0.97	1.33	1.80	2.39	3.12
Case 20	0.04	0.08	0.12	0.17	0.24	0.33	0.45	0.61	0.80	1.05	0.09	0.18	0.27	0.39	0.55	0.76	1.05	1.41	1.87	2.45
Case 21	0.03	0.06	0.10	0.14	0.20	0.27	0.37	0.50	0.67	0.87	0.10	0.19	0.29	0.42	0.59	0.82	1.12	1.51	2.00	2.62
Case 22	0.03	0.06	0.10	0.14	0.19	0.27	0.37	0.49	0.66	0.86	0.11	0.22	0.34	0.49	0.69	0.95	1.30	1.75	2.33	3.04
Case 23	0.03	0.06	0.10	0.14	0.20	0.26	0.38	0.51	0.68	0.89	0.09	0.18	0.28	0.41	0.57	0.79	1.08	1.46	1.94	2.54
Case 24	0.04	0.08	0.13	0.18	0.26	0.36	0.49	0.66	0.88	1.15	0.22	0.43	0.67	0.96	1.35	1.87	2.56	3.46	4.59	6.00
Case 25	0.03	0.06	0.09	0.14	0.19	0.26	0.36	0.49	0.65	0.85	0.12	0.24	0.36	0.52	0.74	1.02	1.40	1.88	2.50	3.27
Case 26	0.02	0.04	0.05	0.10	0.18	0.26	0.40	0.49	0.59	0.62	0.08	0.15	0.23	0.45	0.76	1.13	1.71	2.12	2.52	2.68
Case 27	0.03	0.06	0.10	0.15	0.21	0.30	0.42	0.56	0.72	0.90	0.12	0.24	0.37	0.57	0.83	1.18	1.65	2.18	2.81	3.51
Case 28	0.06	0.11	0.18	0.25	0.36	0.50	0.68	0.92	1.22	1.59	0.16	0.31	0.48	0.69	0.97	1.35	1.84	2.48	3.30	4.31
Case 29	0.07	0.14	0.22	0.32	0.44	0.62	0.84	1.14	1.51	1.97	0.14	0.27	0.42	0.60	0.85	1.17	1.60	2.16	2.88	3.76
Case 30	0.03	0.06	0.10	0.14	0.20	0.28	0.38	0.52	0.68	0.89	0.13	0.25	0.39	0.57	0.80	1.10	1.51	2.04	2.71	3.54
Case 31	0.06	0.11	0.17	0.24	0.34	0.47	0.64	0.86	1.15	1.50	0.16	0.32	0.49	0.71	1.00	1.38	1.89	2.55	3.39	4.43
Case 32	0.06	0.13	0.19	0.28	0.39	0.55	0.75	1.01	1.34	1.75	0.18	0.34	0.53	0.76	1.07	1.48	2.02	2.73	3.63	4.74
Case 33	0.07	0.14	0.22	0.32	0.45	0.63	0.86	1.16	1.54	2.01	0.22	0.44	0.67	0.97	1.37	1.90	2.60	3.50	4.65	6.08
Case 34	0.07	0.14	0.21	0.31	0.43	0.60	0.82	1.10	1.46	1.91	0.17	0.32	0.50	0.71	1.01	1.39	1.91	2.57	3.42	4.47
Case 35	0.06	0.12	0.19	0.27	0.39	0.54	0.73	0.99	1.31	1.72	0.15	0.29	0.45	0.65	0.92	1.28	1.75	2.36	3.13	4.09
Case 36	0.07	0.14	0.21	0.30	0.42	0.59	0.80	1.08	1.44	1.88	0.16	0.31	0.47	0.68	0.96	1.33	1.82	2.46	3.26	4.27
Case 37	0.03	0.06	0.09	0.13	0.19	0.26	0.35	0.47	0.63	0.82	0.09	0.18	0.28	0.40	0.56	0.78	1.07	1.44	1.92	2.51
Case 38	0.03	0.06	0.10	0.14	0.20	0.27	0.37	0.50	0.67	0.88	0.10	0.20	0.31	0.44	0.62	0.86	1.18	1.59	2.12	2.77
Case 39	0.04	0.07	0.11	0.16	0.22	0.31	0.43	0.58	0.76	1.00	0.13	0.25	0.39	0.56	0.79	1.09	1.50	2.02	2.68	3.51
Case 40	0.01	0.02	0.03	0.05	0.07	0.09	0.13	0.17	0.23	0.30	0.04	0.09	0.13	0.19	0.27	0.37	0.51	0.69	0.92	1.20
Case 41	0.03	0.05	0.08	0.11	0.16	0.22	0.30	0.41	0.55	0.71	0.07	0.14	0.22	0.31	0.44	0.61	0.84	1.13	1.50	1.97
Case 42	0.03	0.06	0.10	0.14	0.20	0.28	0.38	0.51	0.68	0.89	0.10	0.19	0.30	0.43	0.60	0.83	1.14	1.53	2.03	2.66
Case 43	0.03	0.07	0.10	0.15	0.21	0.29	0.39	0.63	0.70	0.91	0.09	0.17	0.26	0.37	0.52	0.72	0.98	1.32	1.76	2.30
Case 44	0.04	0.07	0.11	0.17	0.23	0.32	0.44	0.60	0.79	1.04	0.12	0.24	0.37	0.53	0.75	1.04	1.42	1.92	2.55	3.33
Case 45	0.03	0.05	0.08	0.12	0.17	0.23	0.31	0.42	0.56	0.74	0.13	0.25	0.38	0.55	0.78	1.08	1.48	1.99	2.64	3.46
Case 46	0.02	0.04	0.07	0.10	0.14	0.19	0.26	0.35	0.47	0.61	0.10	0.20	0.31	0.45	0.63	0.88	1.20	1.62	2.15	2.81
Case 47	0.02	0.04	0.06	0.09	0.13	0.17	0.24	0.32	0.43	0.56	0.09	0.18	0.27	0.40	0.56	0.77	1.06	1.43	1.89	2.48
Case 48	0.03	0.07	0.10	0.15	0.20	0.28	0.39	0.52	0.69	0.91	0.16	0.31	0.47	0.68	0.95	1.32	1.81	2.44	3.25	4.24
Case 49	0.03	0.05	0.08	0.12	0.16	0.23	0.31	0.42	0.56	0.73	0.13	0.25	0.38	0.55	0.78	1.08	1.48	2.00	2.65	3.47
Case 50	0.03	0.06	0.09	0.12	0.17	0.24	0.33	0.44	0.59	0.77	0.10	0.20	0.31	0.44	0.62	0.87	1.19	1.60	2.12	2.78
Case 51	0.03	0.07	0.10	0.15	0.21	0.29	0.40	0.54	0.72	0.94	0.12	0.23	0.36	0.52	0.72	1.00	1.37	1.85	2.48	3.22
Case 52	0.03	0.07	0.10	0.15	0.21	0.28	0.39	0.53	0.70	0.91	0.19	0.37	0.57	0.82	1.15	1.59	2.18	2.94	3.90	5.10
Case 53	0.03	0.06	0.09	0.13	0.18	0.26	0.35	0.47	0.63	0.82	0.09	0.17	0.26	0.38	0.53	0.74	1.01	1.36	1.81	2.36
Case 54	0.03	0.06	0.09	0.13	0.19	0.26	0.36	0.49	0.64	0.84	0.15	0.29	0.44	0.64	0.90	1.24	1.70	2.30	3.05	3.98
Case 55	0.03	0.06	0.09	0.13	0.18	0.25	0.34	0.46	0.61	0.80	0.13	0.24	0.38	0.54	0.76	1.06	1.45	1.95	2.59	3.39
Case 56	0.04	0.07	0.11	0.16	0.22	0.30	0.42	0.56	0.74	0.97	0.08	0.16	0.25	0.35	0.50	0.69	0.94	1.27	1.69	2.21
Case 57	0.03	0.06	0.09	0.13	0.18	0.25	0.34	0.46	0.62	0.81	0.15	0.28	0.44	0.63	0.88	1.22	1.68	2.26	3.00	3.92
Case 58	0.04	0.07	0.11	0.15	0.21	0.30	0.41	0.55	0.73	0.95	0.13	0.26	0.40	0.57	0.80	1.11	1.52	2.05	2.73	3.57
Cese 59	0.01	0.01	0.02	0.03	0.05	0.06	0.09	0.12	0.16	0.21	0.05	0.09	0.14	0.20	0.29	0.40	0.54	0.73	0.97	1.27
Case 60	0.03	0.06	0.09	0.13	0.18	0.25	0.34	0.48	0.61	0.80	0.09	0.18	0.27	0.39	0.55	0.76	1.05	1.41	1.87	2.45
Case 61	0.04	0.07	0.11	0.15	0.22	0.30	0.41	0.56	0.74	0.97	0.16	0.31	0.48	0.70	0.98	1.36	1.86	2.61	3.33	4.36
Case 62	0.18	0.35	0.53	0.77	1.08	1.50	2.05	2.77	3.68	4.81	0.47	0.91	1.40	2.02	2.84	3.94	5.39	7.27	9.65	12.61
Case 63	0.11	0.22	0.34	0.48	0.68	0.94	1.29	1.74	2.31	3.02	0.34	0.66	1.01	1.46	2.06	2.85	3.90	5.26	6.99	9.13
Case 64	0.05	0.09	0.15	0.21	0.29	0.41	0.56	0.75	1.00	1.31	0.17	0.33	0.51	0.73	1.02	1.42	1.94	2.62	3.48	4.55
Case 65	0.07	0.14	0.21	0.30	0.42	0.59	0.80	1.08	1.44	1.88	0.17	0.32	0.60	0.72	1.02	1.41	1.93	2.60	3.45	4.51
Case 66	0.17	0.32	0.50	0.72	1.01	1.40	1.91	2.58	3.42	4.47	0.43	0.83	1.28	1.84	2.59	3.59	4.91	6.63	8.81	11.51
Case 67	0.10	0.20	0.31	0.45	0.64	0.88	1.21	1.63	2.16	2.83	0.32	0.63	0.97	1.40	1.97	2.73	3.74	5.05	6.70	8.76
Case 68	0.05	0.09	0.15	0.21	0.29	0.41	0.56	0.76	1.00	1.31	0.14	0.26	0.41	0.59	0.83	1.15	1.57	2.12	2.81	3.68
Case 69	0.03	0.05	0.08	0.12	0.16	0.22	0.31	0.41	0.55	0.72	0.14	0.26	0.41	0.59	0.82	1.14	1.56	2.11	2.80	3.66
Case 70	0.01	0.02	0.04	0.05	0.08	0.10	0.14	0.19	0.26	0.34	0.06	0.12	0.19	0.27	0.39	0.64	0.73	0.99	1.31	1.72
Case 71	0.03	0.05	0.08	0.12	0.16	0.23	0.31	0.42	0.55	0.72	0.16	0.31	0.48	0.69	0.97	1.34	1.83	2.47	3.28	4.29
Case 72	0.02	0.05	0.07	0.11	0.15	0.21	0.29	0.39	0.52	0.68	0.13	0.26	0.40	0.57	0.80	1.11	1.52	2.05	2.73	3.56
Case 73	0.02	0.04	0.06	0.08	0.12	0.16	0.22	0.30	0.40	0.52	0.08	0.15	0.23	0.33	0.46	0.64	0.87	1.18	1.57	2.05
Case 74	0.02	0.05	0.07	0.11	0.15	0.21	0.29	0.39	0.51	0.67	0.13	0.25	0.39	0.56	0.78	1.08	1.48	2.00	2.66	3.48
Case 75	0.02	0.05	0.07	0.11	0.15	0.21	0.29	0.39	0.51	0.67	0.13	0.25	0.39	0.56	0.78	1.08	1.48	2.00	2.66	3.48
Case 76	0.03	0.06	0.09	0.12	0.17	0.24	0.33	0.45	0.59	0.78	0.12	0.24	0.37	0.53	0.75	1.04	1.42	1.91	2.54	3.32
Case 77	0.03	0.05	0.08	0.11	0.16	0.22	0.30	0.41	0.54	0.71	0.10	0.19	0.30	0.43	0.60	0.84	1.14	1.54	2.05	2.68
Case 78	0.03	0.06	0.09	0.12	0.17	0.24	0.33	0.45	0.59	0.78	0.11	0.21	0.33	0.48	0.67	0.93	1.27	1.71	2.28	2.98
Case 79	0.04	0.08	0.13	0.18	0.26	0.36	0.49	0.66	0.87	1.14	0.10	0.20	0.30	0.44	0.62	0.86	1.17	1.58	2.10	2.74
Case 80	0.05	0.09	0.14	0.20	0.29	0.40	0.54	0.73	0.97	1.27	0.11	0.21	0.32	0.47	0.65	0.91	1.24	1.68	2.23	2.91
Case 81	0.05	0.09	0.14	0.20	0.28	0.39	0.54	0.72	0.96	1.25	0.14	0.28	0.43	0.63	0.88	1.22	1.67	2.25	2.99	3.91
Case 82	0.06	0.12	0.18	0.26	0.37	0.51	0.70	0.94	1.25	1.63	0.17	0.34	0.52	0.75	1.05	1.46	2.00	2.69	3.58	4.67
Case 83	0.09	0.17	0.26	0.38	0.53	0.73	1.00	1.35	1.79	2.34	0.21	0.41	0.63	0.91	1.27	1.77	2.42	3.26	4.33	5.67
Case 84	0.08	0.15	0.24	0.34	0.48	0.67	0.91	1.23	1.64	2.14	0.20	0.38	0.59	0.85	1.20	1.67	2.28	3.07	4.08	5.34
Case 85	0.07	0.13	0.21	0.30	0.42	0.58	0.79	1.07	1.42	1.86	0.23	0.45	0.69	1.00	1.41	1.95	2.67	3.60	4.78	6.25
Case 86	0.06	0.13	0.19	0.28	0.39	0.56	0.75	1.01	1.34	1.75	0.19	0.38	0.58	0.84	1.18	1.64	2.24	3.03	4.02	5.26
Case 87	0.02	0.05	0.07	0.10	0.14	0.20	0.27	0.36	0.48	0.63	0.07	0.14	0.21	0.30	0.42	0.59	0.81	1.09	1.44	1.89
Case 88	0.02	0.05	0.07	0.11	0.15	0.21	0.29	0.39	0.51	0.67	0.04	0.09	0.13	0.19	0.27	0.38	0.51	0.69	0.92	1.21
Case 89	0.03	0.06	0.10	0.14	0.20	0.27	0.37	0.50	0.67	0.87	0.11	0.22	0.34	0.49	0.69	0.95	1.30	1.75	2.33	3.04
Case 90	0.04	0.07	0.11	0.16	0.23	0.31	0.43	0.58	0.77	1.01	0.15	0.28	0.44	0.63	0.88	1.22	1.68	2.26	3.00	3.92
Case 91	0.03	0.06	0.09	0.13	0.18	0.25	0.34	0.46	0.61	0.80	0.10	0.19	0.29	0.41	0.58	0.80	1.10	1.48	1.97	2.57
Case 92	0.02	0.04	0.08	0.09	0.13	0.18	0.25	0.33	0.44	0.58	0.08	0.15	0.24	0.34	0.48	0.66	0.90	1.22	1.62	2.12
Case 93	0.04	0.09	0.13	0.19	0.27	0.38	0.52	0.70	0.93	1.21	0.19	0.37	0.56	0.81	1.14	1.58	2.17	2.92	3.88	5.08
Case 94	0.06	0.12	0.18	0.26	0.37	0.51	0.70	0.95	1.26	1.64	0.17	0.33	0.51	0.74	1.04	1.44	1.97	2.66	3.53	4.62
Case 95	0.04	0.07	0.11	0.16	0.22	0.30	0.42	0.56	0.75	0.98	0.15	0.28	0.44	0.63	0.89	1.23	1.69	2.27	3.02	3.95
Case 96	0.05	0.10	0.16	0.22	0.32	0.44	0.60	0.81	1.07	1.40	0.15	0.28	0.44	0.63	0.89	1.23	1.68	2.27	3.01	3.94
Case 97	0.06	0.11	0.17	0.25	0.35	0.49	0.67	0.90	1.20	1.56	0.15	0.30	0.46	0.66	0.93	1.29	1.76	2.38	3.16	4.13
Case 98	0.04	0.08	0.13	0.19	0.26	0.37	0.50	0.68	0.90	1.17	0.17	0.34	0.52	0.75	1.06	1.46	2.00	2.70	3.59	4.69
Case 99	0.01	0.03	0.04	0.06	0.09	0.12	0.16	0.22	0.29	0.38	0.06	0.12	0.19	0.28	0.39	0.54	0.74	1.00	1.33	1.73
Case 100	0.02	0.04	0.06	0.09	0.13	0.18	0.24	0.32	0.43	0.56	0.10	0.19	0.30	0.43	0.61	0.84	1.16	1.56	2.07	2.71
Case 101	0.15	0.29	0.44	0.64	0.90	1.25	1.71	2.30	3.06	4.00	0.41	0.80	1.24	1.78	2.51	3.48	4.76	6.42	8.53	11.15

Table 3.05 Room NH_3 Concentrations for 10 Days with Increased Cage Temperature

	Day by day cage average NH3										Day by day cage maximum NH3									
Case Name	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
Basecase	1.12	2.18	3.37	4.85	6.83	9.47	12.96	17.48	23.21	30.34	1.63	3.17	4.89	7.05	9.91	13.74	18.81	25.37	33.70	44.05
Case 02	0.89	1.72	2.66	3.83	5.39	7.47	10.22	13.79	18.31	23.94	1.29	2.51	3.87	5.57	7.84	10.87	14.87	20.06	26.65	34.83
Case 03	0.82	1.59	2.45	3.53	4.96	6.88	9.41	12.70	16.87	22.05	1.34	2.61	4.03	5.81	8.16	11.32	15.50	20.90	27.76	36.29
Case 04	0.89	1.73	2.67	3.84	5.40	7.49	10.26	13.84	18.38	24.02	1.19	2.32	3.58	5.16	7.26	10.07	13.78	18.59	24.69	32.27
Case 05	0.91	1.78	2.72	3.92	5.51	7.64	10.46	14.11	18.74	24.50	1.21	2.36	3.64	5.25	7.38	10.23	14.00	18.89	25.09	32.80
Case 06	0.86	1.67	2.58	3.72	5.22	7.24	9.92	13.37	17.76	23.22	1.38	2.68	4.13	5.95	8.37	11.60	15.88	21.42	28.44	37.18
Case 07	1.21	2.35	3.62	5.22	7.34	10.18	13.94	18.80	24.97	32.63	1.76	3.43	5.28	7.61	10.71	14.85	20.32	27.41	36.40	47.59
Case 08	0.97	1.89	2.92	4.21	5.92	8.21	11.23	15.15	20.12	26.30	1.37	2.67	4.12	5.93	8.34	11.57	15.83	21.36	28.37	37.08
Case 09	0.90	1.75	2.69	3.88	5.46	7.57	10.36	13.97	18.55	24.25	1.52	2.97	4.57	6.59	9.27	12.86	17.60	23.74	31.53	41.21
Case 10	1.10	2.14	3.31	4.77	6.70	9.29	12.72	17.15	22.78	29.78	1.67	3.24	5.00	7.20	10.13	14.04	19.22	25.92	34.43	45.00
Case 11	1.10	2.14	3.30	4.76	8.70	9.29	12.71	17.15	22.78	29.77	1.51	2.94	4.53	6.53	9.18	12.73	17.43	23.51	31.22	40.81
Case 12	1.15	2.23	3.45	4.97	6.98	9.68	13.25	17.88	23.75	31.04	1.57	3.06	4.72	6.80	9.56	13.26	18.15	24.48	32.52	42.50
Case 13	1.30	2.52	3.89	5.60	7.88	10.93	14.95	20.17	26.79	35.02	1.56	3.04	4.68	6.75	9.49	13.16	18.01	24.30	32.27	42.19
Case 14	1.15	2.24	3.46	4.98	7.01	9.72	13.30	17.94	23.82	31.14	1.36	2.65	4.09	5.89	8.28	11.49	15.72	21.21	28.16	36.82
Case 15	1.10	2.14	3.31	4.77	6.70	9.29	12.72	17.15	22.78	29.78	1.67	3.24	5.00	7.20	10.13	14.04	19.22	25.92	34.43	45.00
Case 16	1.15	2.24	3.45	4.98	7.00	9.71	13.29	17.92	23.80	31.11	1.63	3.16	4.88	7.03	9.89	13.71	18.76	25.31	33.62	43.95
Case 17	0.94	1.84	2.83	4.08	5.74	7.96	10.89	14.69	19.52	25.51	1.28	2.49	3.84	5.54	7.79	10.81	14.79	19.95	26.49	34.63
Case 18	0.93	1.81	2.79	4.03	5.67	7.86	10.75	14.50	19.26	25.18	1.27	2.47	3.80	5.48	7.70	10.68	14.62	19.72	26.19	34.24
Case 19	0.90	1.75	2.69	3.88	5.46	7.57	10.36	13.97	18.58	24.26	1.22	2.38	3.67	5.29	7.44	10.32	14.13	19.06	25.31	33.08
Case 20	0.86	1.68	2.58	3.72	5.24	7.26	9.94	13.41	17.81	23.28	1.22	2.38	3.67	5.29	7.44	10.32	14.12	19.05	25.30	33.07
Case 21	0.94	1.83	2.82	4.07	5.72	7.93	10.85	14.64	19.44	25.42	1.33	2.59	3.99	5.75	8.08	11.21	15.34	20.69	27.48	35.92
Case 22	0.87	1.69	2.60	3.75	5.27	7.30	10.00	13.48	17.91	23.41	1.36	2.66	4.09	5.90	8.30	11.51	15.75	21.24	28.21	36.88
Case 23	0.86	1.67	2.58	3.71	5.22	7.24	9.91	13.37	17.76	23.22	1.33	2.58	3.98	5.74	8.07	11.19	15.32	20.67	27.45	35.88
Case 24	0.98	1.91	2.94	4.24	5.96	8.26	11.30	15.25	20.25	26.47	1.57	3.06	4.72	6.80	9.56	13.26	18.14	24.47	32.50	42.49
Case 25	1.56	3.04	4.89	6.77	9.51	13.19	18.05	24.35	32.35	42.28	2.05	3.99	6.15	8.86	12.46	17.28	23.64	31.89	42.36	55.37
Case 26	2.12	4.02	6.20	11.92	20.30	30.25	45.71	56.48	67.24	71.52	2.58	4.90	7.55	14.51	24.70	36.81	55.62	68.72	81.82	87.03
Case 27	1.66	3.21	4.95	7.53	11.06	15.62	21.95	28.91	37.36	46.66	2.38	4.61	7.11	10.82	15.90	22.45	31.55	41.57	53.72	67.08
Case 28	0.91	1.77	2.73	3.93	5.53	7.67	10.50	14.16	18.81	24.59	1.41	2.74	4.22	6.08	8.56	11.86	16.24	21.90	29.09	38.02
Case 29	0.92	1.79	2.75	3.97	5.58	7.74	10.59	14.28	18.97	24.80	1.33	2.59	3.99	5.75	8.08	11.21	15.34	20.70	27.49	35.93
Case 30	0.87	1.69	2.60	3.75	5.27	7.31	10.01	13.50	17.93	23.44	1.34	2.61	4.02	5.79	8.15	11.30	15.47	20.86	27.71	36.22
Case 31	1.01	1.96	3.02	4.36	6.13	8.50	11.63	15.69	20.84	27.25	1.48	2.87	4.43	6.38	8.98	12.45	17.04	22.99	30.53	39.90
Case 32	0.91	1.77	2.73	3.93	5.53	7.66	10.49	14.15	18.79	24.57	1.45	2.82	4.35	6.27	8.82	12.23	16.74	22.59	30.00	39.21
Case 33	1.03	2.00	3.08	4.44	6.24	8.66	11.85	15.98	21.23	27.75	1.63	3.17	4.89	7.05	9.91	13.74	18.81	25.37	33.69	44.04
Case 34	0.99	1.92	2.96	4.26	6.00	8.31	11.38	15.35	20.39	26.65	1.40	2.72	4.20	6.05	8.50	11.79	16.14	21.77	28.91	37.80
Case 35	0.92	1.78	2.75	3.96	5.57	7.72	10.57	14.26	18.93	24.75	1.40	2.72	4.20	6.05	8.51	11.80	16.16	21.79	28.94	37.83
Case 36	0.98	1.90	2.93	4.22	5.94	8.24	11.27	15.20	20.19	26.40	1.35	2.63	4.05	5.83	8.20	11.38	15.57	21.00	27.89	36.46
Case 37	0.89	1.74	2.68	3.86	5.43	7.52	10.30	13.89	18.45	24.11	1.17	2.27	3.50	5.05	7.10	9.84	13.47	18.17	24.13	31.54
Case 38	0.92	1.80	2.77	3.99	5.62	7.79	10.66	14.38	19.10	24.96	1.39	2.70	4.16	6.00	8.43	11.69	16.00	21.58	28.67	37.47
Case 39	0.96	1.87	2.88	4.16	5.85	8.11	11.09	14.96	19.88	25.98	1.40	2.72	4.19	6.04	8.49	11.77	16.11	21.73	28.87	37.73
Case 40	1.03	2.00	3.08	4.44	6.25	8.66	11.86	16.00	21.24	27.77	1.45	2.81	4.34	6.25	8.79	12.19	16.68	22.50	29.88	39.06
Case 41	0.88	1.71	2.64	3.80	5.35	7.41	10.15	13.69	18.18	23.76	1.24	2.41	3.71	5.35	7.53	10.44	14.29	19.28	25.60	33.47
Case 42	0.90	1.75	2.70	3.89	5.47	7.58	10.37	13.99	18.58	24.29	1.32	2.57	3.96	5.70	8.02	11.12	15.22	20.52	27.26	35.63
Case 43	0.97	1.88	2.90	4.17	5.87	8.14	11.14	15.02	19.95	26.08	1.26	2.46	3.79	5.46	7.68	10.65	14.58	19.67	26.12	34.15
Case 44	1.10	2.14	3.31	4.78	6.70	9.29	12.71	17.15	22.78	29.77	1.42	2.77	4.26	6.16	8.64	11.98	16.40	22.12	29.38	38.41
Case 45	1.00	1.95	3.01	4.34	6.10	8.46	11.58	15.62	20.74	27.11	1.39	2.71	4.18	6.03	8.48	11.76	16.09	21.71	28.83	37.69
Case 46	1.01	1.97	3.03	4.37	6.14	8.52	11.66	15.73	20.89	27.31	1.43	2.78	4.28	6.18	8.68	12.04	16.48	22.23	29.53	38.60
Case 47	1.02	1.98	3.06	4.41	6.20	8.60	11.77	15.88	21.09	27.56	1.46	2.84	4.38	6.31	8.87	12.30	16.84	22.72	30.17	39.44
Case 48	1.09	2.12	3.28	4.72	6.64	9.21	12.60	17.00	22.57	29.51	1.41	2.75	4.24	6.11	8.59	11.91	16.29	21.98	29.19	38.16
Case 49	1.05	2.05	3.16	4.55	6.41	8.88	12.16	16.40	21.78	28.47	1.40	2.72	4.19	6.03	8.49	11.77	16.10	21.72	28.85	37.71
Case 50	0.96	1.86	2.87	4.14	5.82	8.07	11.05	14.90	19.79	25.87	1.35	2.63	4.05	5.83	8.20	11.38	15.57	21.00	27.89	36.46
Case 51	1.06	2.07	3.19	4.60	6.47	8.97	12.27	16.56	21.99	28.75	1.41	2.74	4.23	6.09	8.57	11.88	16.26	21.94	29.14	38.09
Case 52	0.87	1.69	2.60	3.75	5.27	7.30	10.00	13.48	17.91	23.41	1.36	2.66	4.09	5.90	8.30	11.51	15.75	21.24	28.21	36.88
Case 53	1.15	2.24	3.45	4.97	7.00	9.70	13.28	17.91	23.79	31.09	1.47	2.86	4.41	6.36	8.94	12.39	16.96	22.88	30.39	39.72
Case 54	0.97	1.89	2.92	4.20	5.91	8.20	11.22	15.14	20.10	26.28	1.39	2.71	4.18	6.02	8.47	11.74	16.07	21.68	28.79	37.64
Case 55	1.06	2.06	3.18	4.59	6.45	8.94	12.24	16.51	21.93	28.67	1.36	2.66	4.09	5.90	8.30	11.51	15.75	21.24	28.21	36.88
Case 56	0.98	1.91	2.94	4.24	5.96	8.27	11.32	15.27	20.28	26.51	1.34	2.60	4.01	5.78	8.13	11.27	15.43	20.81	27.64	36.14
Case 57	0.96	1.88	2.89	4.17	5.87	8.14	11.13	15.02	19.95	26.08	1.43	2.77	4.28	6.17	8.67	12.02	16.46	22.20	29.48	38.54
Case 58	1.03	2.01	3.10	4.47	6.29	8.73	11.94	16.11	21.40	27.97	1.49	2.90	4.48	6.45	9.07	12.58	17.22	23.23	30.85	40.33
Case 59	1.12	2.19	3.37	4.86	6.84	9.48	12.97	17.50	23.24	30.39	1.42	2.77	4.27	6.16	8.66	12.01	16.44	22.18	29.45	38.50
Case 60	1.22	2.38	3.67	5.29	7.45	10.32	14.13	19.06	25.32	33.09	1.52	2.96	4.57	6.59	9.27	12.85	17.58	23.72	31.60	41.18
Case 61	1.06	2.07	3.19	4.59	6.46	8.96	12.26	16.54	21.96	28.71	1.47	2.86	4.41	6.35	8.93	12.39	16.95	22.87	30.37	39.70
Case 62	1.21	2.35	3.63	5.23	7.36	10.20	13.96	18.83	25.01	32.69	1.76	3.43	5.29	7.62	10.72	14.86	20.34	27.44	38.44	47.64
Case 63	1.08	2.11	3.25	4.68	6.58	9.13	12.49	16.85	22.38	29.25	1.77	3.44	5.31	7.65	10.76	14.92	20.42	27.55	36.59	47.83
Case 64	0.94	1.83	2.82	4.07	5.72	7.93	10.85	14.64	19.44	25.42	1.36	2.65	4.09	5.89	8.28	11.48	15.71	21.20	28.15	36.80
Case 65	1.04	2.03	3.12	4.50	6.33	8.78	12.02	16.21	21.53	28.15	1.64	3.19	4.91	7.08	9.96	13.81	18.90	25.49	33.86	44.26
Case 66	1.21	2.35	3.62	5.21	7.33	10.17	13.91	18.77	24.92	32.58	1.80	3.51	5.41	7.80	10.97	15.21	20.82	28.08	37.30	48.76
Case 67	1.11	2.17	3.34	4.82	6.78	9.40	12.87	17.36	23.05	30.13	1.77	3.45	5.31	7.66	10.77	14.93	20.43	27.57	36.61	47.86
Case 68	0.96	1.86	2.87	4.13	5.81	8.06	11.03	14.89	19.77	25.84	1.51	2.93	4.52	6.52	9.17	12.71	17.40	23.47	31.17	40.75
Case 69	0.91	1.77	2.73	3.94	5.54	7.68	10.51	14.17	18.82	24.61	1.34	2.61	4.03	5.81	8.17	11.33	15.50	20.91	27.77	36.30
Case 70	1.02	1.98	3.05	4.40	6.18	8.58	11.74	15.83	21.03	27.49	1.43	2.77	4.28	6.16	8.67	12.02	16.45	22.19	29.48	38.53
Case 71	1.02	1.99	3.07	4.43	6.22	8.63	11.81	15.93	21.16	27.66	1.40	2.72	4.19	6.03	8.49	11.77	16.10	21.72	28.85	37.71
Case 72	0.93	1.81	2.79	4.03	5.66	7.85	10.74	14.49	19.25	25.16	1.38	2.69	4.15	5.99	8.42	11.68	15.98	21.56	28.63	37.43
Case 73	1.02	1.99	3.07	4.42	6.22	8.62	11.80	15.92	21.14	27.63	1.41	2.73	4.22	6.08	8.54	11.85	16.22	21.87	29.05	37.98
Case 74	0.98	1.91	2.94	4.24	5.96	8.27	11.31	15.26	20.27	26.49	1.37	2.66	4.11	5.92	8.33	11.55	15.80	21.32	28.32	37.01
Case 75	0.96	1.86	2.87	4.14	5.82	8.07	11.04	14.89	19.78	25.85	1.36	2.65	4.09	5.90	8.29	11.50	15.74	21.23	28.20	36.86
Case 76	0.97	1.88	2.90	4.18	5.87	8.15	11.15	15.04	19.97	26.11	1.27	2.46	3.80	5.48	7.70	10.68	14.62	19.72	26.19	34.23
Case 77	0.98	1.90	2.93	4.23	5.95	8.25	11.29	15.23	20.23	26.44	1.38	2.68	4.14	5.97	8.39	11.63	15.92	21.47	28.52	37.28
Case 78	1.00	1.94	2.99	4.32	6.07	8.42	11.52	15.54	20.64	26.98	1.37	2.66	4.10	5.90	8.30	11.51	15.76	21.25	28.23	36.90
Case 79	0.86	1.67	2.57	3.70	5.21	7.22	9.88	13.33	17.71	23.15	1.22	2.38	3.67	5.30	7.45	10.33	14.13	19.07	25.32	33.10
Case 80	0.89	1.73	2.66	3.84	5.40	7.49	10.24	13.82	18.35	23.99	1.40	2.72	4.19	6.05	8.50	11.79	16.14	21.77	28.91	37.79
Case 81	0.91	1.76	2.72	3.92	5.51	7.64	10.45	14.10	18.72	24.47	1.41	2.75	4.24	6.12	8.60	11.93	16.33	22.03	29.25	38.24
Case 82	0.87	1.69	2.60	3.75	5.27	7.31	10.00	13.50	17.92	23.43	1.45	2.83	4.36	6.29	8.84	12.26	16.77	22.63	30.05	39.28
Case 83	0.91	1.78	2.74	3.95	5.55	7.70	10.54	14.22	18.88	24.68	1.57	3.06	4.72	6.80	9.56	13.26	18.14	24.48	32.51	42.49
Case 84	0.96	1.88	2.89	4.17	5.86	8.13	11.12	15.00	19.93	26.05	1.54	3.00	4.62	6.87	9.37	13.00	17.79	24.00	31.87	41.66
Case 85	1.00	1.95	3.01	4.34	6.11	8.47	11.59	15.63	20.76	27.14	1.48	2.87	4.43	6.39	8.98	12.46	17.05	23.00	30.54	39.93
Case 86	1.00	1.94	2.99	4.31	6.06	8.41	11.51	15.52	20.62	26.95	1.69	3.29	5.07	7.31	10.28	14.25	19.50	26.31	34.94	45.67
Case 87	0.72	1.41	2.17	3.13	4.40	6.10	8.35	11.26	14.96	19.55	1.37	2.67	4.12	5.93	8.34	11.57	15.84	21.36	28.37	37.09
Case 88	0.81	1.57	2.42	3.49	4.90	6.80	9.30	12.65	16.67	21.78	1.31	2.55	3.93	5.66	7.96	11.04	15.10	20.37	27.06	35.37
Case 89	0.85	1.66	2.55	3.68	5.17	7.17	9.82	13.25	17.59	23.00	1.35	2.63	4.05	5.85	8.22	11.40	15.60	21.04	27.95	36.53
Case 90	0.87	1.69	2.61	3.76	5.29	7.34	10.04	13.55	17.99	23.52	1.31	2.54	3.92	5.65	7.94	11.01	15.07	20.33	27.00	35.30
Case 91	0.89	1.73	2.67	3.84	5.41	7.50	10.26	13.84	18.38	24.02	1.37	2.68	4.12	5.95	8.36	11.59	15.87	21.40	28.43	37.16
Case 92	0.85	1.65	2.55	3.67	5.16	7.16	9.79	13.21	17.54	22.93	1.25	2.43	3.75	5.41	7.60	10.55	14.43	19.47	25.86	33.80
Case 93	0.95	1.84	2.84	4.10	5.76	7.99	10.93	14.75	19.59	25.61	1.45	2.81	4.34	6.25	8.79	12.19	16.69	22.51	29.90	39.08
Case 94	0.91	1.78	2.74	3.95	5.56	7.71	10.55	14.23	18.90	24.70	1.42	2.77	4.27	6.15	8.65	11.99	16.41	22.14	29.40	38.43
Case 95	0.95	1.84	2.84	4.10	5.76	7.99	10.93	14.75	19.59	25.61	1.45	2.81	4.34	6.25	8.79	12.19	16.69	22.51	29.90	39.08
Case 96	1.02	1.98	3.05	4.40	6.19	8.58	11.74	15.84	21.04	27.51	1.44	2.80	4.31	6.21	8.74	12.12	16.58	22.37	29.71	38.84
Case 97	0.90	1.75	2.69	3.88	5.46	7.57	10.35	13.97	18.55	24.25	1.50	2.92	4.50	6.49	9.13	12.65	17.32	23.36	31.03	40.56
Case 98	1.02	1.98	3.05	4.40	6.18	8.57	11.73	15.83	21.02	27.48	1.41	2.74	4.23	6.10	8.68	11.89	16.28	21.96	29.17	38.12
Case 99	1.03	2.01	3.10	4.46	6.28	8.70	11.91	16.07	21.34	27.89	1.54	3.00	4.62	6.66	9.36	12.98	17.76	23.96	31.82	41.60
Case 100	0.90	1.75	2.70	3.89	5.47	7.59	10.38	14.01	18.61	24.32	1.72	3.35	5.16	7.43	10.46	14.50	19.84	26.77	35.55	46.47
Case 101	1.25	2.43	3.74	5.40	7.59	10.53	14.40	19.43	25.81	33.74	1.83	3.56	6.50	7.92	11.14	15.45	21.14	28.51	37.87	49.50

Table 3.06 Cage NH_3 Concentrations for 10 Days with Increased Cage Temperature

3.3 Ranking of Whole Room Simulations

The following tables (3.07 to 3.14) present rankings of the results of the CFD room simulations based on room (scientist's breathing zone) and cage mean values for temperature, relative humidity, and CO_2 and NH_3 (day 4) concentrations. The tables start with the case with the lowest value and list the rest in ascending order. In addition to the case number, which should be used to identify all details of the case, the supply diffuser type, exhaust location, supply flow rate, and supply discharge temperature are given to provide a quick overview of the case.

Tables 3.07 and 3.08 for temperature show the ceiling exhausts produce lower temperatures in both the room and cages, ignoring the two 5 ACH cases which start with very low supply temperatures. Tables 3.09 and 3.10 for relative humidity show that the low exhaust cases seem to dominate the table producing low humidity. This is also a consequence of the low exhaust rooms and cages being warmer than the ceiling and high level exhausts.

Table 3.11 showing room breathing zone CO_2 concentration shows the ceiling and high level exhausts producing the lowest values. The overall variation is very small in absolute terms. It is interesting to see that the first 20 ACH case comes 50th in the list. This indicates that with the right design it is possible to ventilate a room better than by simply providing more air.

Table 3.12 showing CO_2 concentration in the cages also shows relatively small variations across the cases. No particular configuration presents itself as always performing better than the others.

Tables 3.13 and 3.14 show NH_3 concentrations in the room and cages on day 4. The room data shows no particular pattern. The cage data shows rather more low exhaust cases giving low values, which is due to the higher temperature and related lower relative humidity reducing the actual NH_3 generation rate.

In all of the ranking tables, no single configuration proves to be superior in all respects. This further illustrates that the airflow patterns and thus the ventilation of the room and the cages depends on the complex interaction of all of features in the room.

Table 3.07 Ranking of Cases with respect to Room Temperature

Case Name	Supply Diffuser Type	Exhaust Location and Number	Supply ACH	Supply Temperature (°C)	Supply Temperature (°F)	Room Temp (°C)	Room Temp (°F)
Case 66	Low Ind	Low	5	6.6	43.9	18.6	65.6
Case 62	Low Ind	Low	5	6.6	43.9	19.1	66.5
Case 53	Radial	Ceiling	15	18.8	65.8	19.8	67.6
Case 55	Low Ind	Ceiling	15	18.8	65.8	19.8	67.6
Case 54	Slot	Ceiling	15	18.8	65.8	19.8	67.6
Case 36	Low Ind	Ceiling	15	17.5	63.5	19.9	67.8
Case 35	Slot	Ceiling	15	17.5	63.5	20.0	67.9
Case 34	Radial	Ceiling	15	17.5	63.5	20.0	67.9
Case 07	Low Ind	Ceiling	15	18.8	65.8	20.0	67.9
Case 98	Low ind	Ceiling	15	17.5	63.5	20.0	68.0
Case 96	Radial	Ceiling	15	17.5	63.5	20.0	68.0
Case 97	Slot	Ceiling	15	17.5	63.5	20.0	68.0
Case 16	Radial	Ceiling	15	18.8	65.8	20.1	68.1
Case 46	Radial	Ceiling	15	18.8	65.8	20.2	68.3
Case 67	Low Ind	Low	10	14.8	58.6	20.2	68.3
Case 19	Radial	Ceiling	15	18.8	65.8	20.2	68.4
Case 18	Low Ind	Ceiling	15	18.8	65.8	20.2	68.4
Case 17	Slot	Ceiling	15	18.8	65.8	20.2	68.4
Case 94	Slot	Ceiling	15	17.5	63.5	20.2	68.4
Case 95	Low Ind	Ceiling	15	17.5	63.5	20.2	68.4
Case 43	Low Ind (rot 90°)	Ceiling	15	18.8	65.8	20.2	68.4
Case 47	Radial	Ceiling	15	18.8	65.8	20.3	68.5
Case 93	Radial	Ceiling	15	17.5	63.5	20.3	68.5
Case 45	Radial	Ceiling	15	18.8	65.8	20.3	68.5
Case 60	Low Ind	High	15	18.8	65.8	20.3	68.5
Basecase	Radial	Ceiling	15	18.8	65.8	20.3	68.5
Case 25	Radial	Ceiling	15	18.8	65.8	20.3	68.5
Case 27	Low Ind	Ceiling	15	18.8	65.8	20.3	68.6
Case 56	Radial	High	15	18.8	65.8	20.3	68.6
Case 59	Slot	Low	15	18.8	65.8	20.3	68.6
Case 63	Low Ind	Low	10	14.8	58.6	20.3	68.6
Case 90	Radial	Ceiling	15	18.8	65.8	20.4	68.7
Case 77	Slot	Ceiling	15	18.8	65.8	20.4	68.7
Case 76	Radial	Ceiling	15	18.8	65.8	20.4	68.7
Case 21	Low Ind	Ceiling	15	18.8	65.8	20.4	68.7
Case 92	Low Ind	Ceiling	15	18.8	65.8	20.4	68.7
Case 26	Slot	Ceiling	15	18.8	65.8	20.4	68.7
Case 78	Low Ind	Ceiling	15	18.8	65.8	20.4	68.7
Case 04	Slot	Ceiling	15	18.8	65.8	20.4	68.8
Case 44	Radial (rot 90°)	Ceiling	15	18.8	65.8	20.4	68.8
Case 91	Slot	Ceiling	15	18.8	65.8	20.5	68.8
Case 50	Radial	Ceiling	15	18.8	65.8	20.5	68.8
Case 52	Radial	Ceiling	15	18.8	65.8	20.5	68.8
Case 08	Low Ind	High	15	18.8	65.8	20.5	68.9
Case 42	Low Ind	Ceiling x4	15	18.8	65.8	20.5	68.9
Case 51	Radial	Ceiling	15	18.8	65.8	20.5	69.0
Case 05	Slot	High	15	18.8	65.8	20.5	69.0
Case 41	Slot	Ceiling x4	15	18.8	65.8	20.5	69.0
Case 40	Radial	Ceiling x4	15	18.8	65.8	20.5	69.0
Case 49	Radial	Ceiling	15	18.8	65.8	20.5	69.0
Case 20	Slot	Ceiling	15	18.8	65.8	20.6	69.0

Case Name	Supply Diffuser Type	Exhaust Location and Number	Supply ACH	Supply Temperature (°C)	Supply Temperature (°F)	Room Temp (°C)	Room Temp (°F)
Case 48	Radial	Ceiling	15	18.8	65.8	20.6	69.1
Case 02	Radial	High	15	18.8	65.8	20.7	69.2
Case 37	Radial	Ceiling/Low 50/50	15	18.8	65.8	20.7	69.3
Case 85	Radial	Low	15	17.5	63.5	20.7	69.3
Case 38	Slot	Ceiling/Low 50/50	15	18.8	65.8	20.8	69.4
Case 39	Low Ind	Ceiling/Low 50/50	15	18.8	65.8	20.8	69.4
Case 65	Low Ind	Low	15	17.5	63.5	20.8	69.5
Case 13	Slot	Low	15	20.7	69.3	20.8	69.5
Case 10	Radial	Ceiling	15	20.7	69.3	20.9	69.7
Case 72	Radial	High x4 / Low x2	15	18.8	65.8	21.1	69.9
Case 74	Low Ind	High x4 / Low x2	15	18.8	65.8	21.1	70.0
Case 75	Radial	Ceiling/Low 50/50	15	18.8	65.8	21.1	70.0
Case 73	Slot	High x4 / Low x2	15	18.8	65.8	21.1	70.0
Case 14	Low Ind	Ceiling	15	20.7	69.3	21.1	70.0
Case 12	Slot	Ceiling	15	20.7	69.3	21.1	70.0
Case 64	Low Ind	Low	20	18.9	66.0	21.2	70.1
Case 86	Slot	Low	15	17.5	63.5	21.2	70.1
Case 29	Low Ind	Low	5	11	51.8	21.2	70.1
Case 15	Low Ind	Low	15	20.7	69.3	21.2	70.2
Case 68	Low Ind	Low	20	18.9	66.0	21.2	70.2
Case 22	Radial	Low	15	18.8	65.8	21.2	70.2
Case 69	Radial	High x4 / Low x4	15	18.8	65.8	21.3	70.3
Case 82	Radial	2 Door exhausts	15	18.8	65.8	21.3	70.3
Case 11	Radial	Low	15	20.7	69.3	21.3	70.4
Case 31	Radial	Low	15	17.5	63.5	21.4	70.5
Case 83	Slot	2 Door exhausts	15	17.5	63.5	21.4	70.6
Case 70	Slot	High x4 / Low x4	15	18.8	65.8	21.4	70.6
Case 84	Low Ind	2 Door exhausts	15	17.5	63.5	21.5	70.7
Case 71	Low Ind	High x4 / Low x4	15	18.8	65.8	21.6	70.8
Case 57	Radial	Low	15	18.8	65.8	21.7	71.1
Case 23	Slot	Low	15	18.8	65.8	21.8	71.2
Case 58	Slot	High	15	18.8	65.8	21.8	71.2
Case 79	Radial	2 Door exhausts	15	18.8	65.8	21.9	71.5
Case 32	Slot	Low	15	17.5	63.5	22.0	71.5
Case 33	Low Ind	Low	15	17.5	63.5	22.0	71.5
Case 61	Low Ind	Low	15	18.8	65.8	22.0	71.7
Case 03	Radial	Low	15	18.8	65.8	22.1	71.7
Case 80	Slot	2 Door exhausts	15	18.8	65.8	22.1	71.8
Case 24	Low Ind	Low	15	18.8	65.8	22.1	71.8
Case 06	Slot	Low	15	18.8	65.8	22.3	72.1
Case 28	Low Ind	Low	10	16.8	62.2	22.3	72.1
Case 81	Low Ind	2 Door exhausts	15	18.8	65.8	22.5	72.4
Case 87	Radial	Low	15	19.2	66.6	22.5	72.4
Case 88	Slot	Low	15	19.2	66.6	22.6	72.6
Case 09	Low Ind	Low	15	18.8	65.8	22.6	72.6
Case 30	Low Ind	Low	20	19.8	67.6	22.6	72.6
Case 89	Low Ind	Low	15	19.2	66.6	22.9	73.3

Table 3.08 Ranking of Cases with respect to Cage Temperature

Case Name	Supply Diffuser Type	Exhaust Location and Number	Supply ACH	Supply Temperature (°C)	Supply Temperature (°F)	Cage Temp (°C)	Cage Temp (°F)
Case 66	Low Ind	Low	5	6.6	43.9	20.6	69.1
Case 62	Low Ind	Low	5	6.6	43.9	20.9	69.6
Case 35	Slot	Ceiling	15	17.5	63.5	21.3	70.4
Case 34	Radial	Ceiling	15	17.5	63.5	21.4	70.4
Case 36	Low Ind	Ceiling	15	17.5	63.5	21.5	70.6
Case 55	Low Ind	Ceiling	15	18.8	65.8	21.6	70.9
Case 97	Slot	Ceiling	15	17.5	63.5	21.6	71.0
Case 54	Slot	Ceiling	15	18.8	65.8	21.7	71.0
Case 53	Radial	Ceiling	15	18.8	65.8	21.7	71.0
Case 98	Low ind	Ceiling	15	17.5	63.5	21.7	71.1
Case 19	Radial	Ceiling	15	18.8	65.8	21.7	71.1
Case 96	Radial	Ceiling	15	17.5	63.5	21.8	71.2
Case 94	Slot	Ceiling	15	17.5	63.5	21.9	71.3
Case 67	Low Ind	Low	10	14.8	58.6	21.9	71.4
Case 75	Radial	Ceiling/Low 50/50	15	18.8	65.8	21.9	71.4
Case 60	Low Ind	High	15	18.8	65.8	21.9	71.4
Case 63	Low Ind	Low	10	14.8	58.6	21.9	71.4
Case 90	Radial	Ceiling	15	18.8	65.8	21.9	71.5
Case 95	Low Ind	Ceiling	15	17.5	63.5	21.9	71.5
Case 93	Radial	Ceiling	15	17.5	63.5	21.9	71.5
Case 92	Low Ind	Ceiling	15	18.8	65.8	22.0	71.6
Case 91	Slot	Ceiling	15	18.8	65.8	22.0	71.6
Case 43	Low Ind (rot 90°)	Ceiling	15	18.8	65.8	22.0	71.6
Case 46	Radial	Ceiling	15	18.8	65.8	22.0	71.6
Case 21	Low Ind	Ceiling	15	18.8	65.8	22.0	71.6
Case 59	Slot	Low	15	18.8	65.8	22.0	71.6
Basecase	Radial	Ceiling	15	18.8	65.8	22.1	71.7
Case 18	Low Ind	Ceiling	15	18.8	65.8	22.1	71.7
Case 45	Radial	Ceiling	15	18.8	65.8	22.1	71.7
Case 17	Slot	Ceiling	15	18.8	65.8	22.1	71.7
Case 20	Slot	Ceiling	15	18.8	65.8	22.1	71.7
Case 47	Radial	Ceiling	15	18.8	65.8	22.1	71.7
Case 78	Low Ind	Ceiling	15	18.8	65.8	22.1	71.8
Case 56	Radial	High	15	18.8	65.8	22.1	71.8
Case 27	Low Ind	Ceiling	15	18.8	65.8	22.1	71.8
Case 48	Radial	Ceiling	15	18.8	65.8	22.1	71.8
Case 76	Radial	Ceiling	15	18.8	65.8	22.1	71.8
Case 26	Slot	Ceiling	15	18.8	65.8	22.1	71.8
Case 77	Slot	Ceiling	15	18.8	65.8	22.1	71.9
Case 44	Radial (rot 90°)	Ceiling	15	18.8	65.8	22.2	71.9
Case 04	Slot	Ceiling	15	18.8	65.8	22.2	71.9
Case 50	Radial	Ceiling	15	18.8	65.8	22.2	71.9
Case 49	Radial	Ceiling	15	18.8	65.8	22.2	71.9
Case 40	Radial	Ceiling x4	15	18.8	65.8	22.2	71.9
Case 42	Low Ind	Ceiling x4	15	18.8	65.8	22.2	71.9
Case 51	Radial	Ceiling	15	18.8	65.8	22.2	71.9
Case 25	Radial	Ceiling	15	18.8	65.8	22.2	72.0
Case 83	Slot	2 Door exhausts	15	17.5	63.5	22.2	72.0
Case 08	Low Ind	High	15	18.8	65.8	22.2	72.0
Case 41	Slot	Ceiling x4	15	18.8	65.8	22.2	72.0
Case 37	Radial	Ceiling/Low 50/50	15	18.8	65.8	22.3	72.1

Case Name	Supply Diffuser Type	Exhaust Location and Number	Supply ACH	Supply Temperature (°C)	Supply Temperature (°F)	Cage Temp (°C)	Cage Temp (°F)
Case 05	Slot	High	15	18.8	65.8	22.3	72.1
Case 82	Radial	2 Door exhausts	15	18.8	65.8	22.3	72.1
Case 86	Slot	Low	15	17.5	63.5	22.3	72.1
Case 02	Radial	High	15	18.8	65.9	22.3	72.2
Case 85	Radial	Low	15	17.5	63.5	22.4	72.3
Case 38	Slot	Ceiling/Low 50/50	15	18.8	65.8	22.4	72.3
Case 39	Low Ind	Ceiling/Low 50/50	15	18.8	65.8	22.4	72.3
Case 65	Low Ind	Low	15	17.5	63.5	22.4	72.4
Case 07	Low Ind	Ceiling	15	18.8	65.8	22.5	72.4
Case 52	Radial	Ceiling	15	18.8	65.8	22.5	72.5
Case 22	Radial	Low	15	18.8	65.8	22.5	72.5
Case 84	Low Ind	2 Door exhausts	15	17.5	63.5	22.5	72.5
Case 72	Radial	High x4 / Low x2	15	18.8	65.8	22.5	72.6
Case 73	Slot	High x4 / Low x2	15	18.8	65.8	22.6	72.7
Case 74	Low Ind	High x4 / Low x2	15	18.8	65.8	22.6	72.7
Case 29	Low Ind	Low	5	11	51.8	22.6	72.8
Case 87	Radial	Low	15	19.2	66.6	22.7	72.8
Case 64	Low Ind	Low	20	18.9	66.0	22.7	72.8
Case 31	Radial	Low	15	17.5	63.5	22.7	72.8
Case 23	Slot	Low	15	18.8	65.8	22.7	72.9
Case 69	Radial	High x4 / Low x4	15	18.8	65.8	22.7	72.9
Case 11	Radial	Low	15	20.7	69.3	22.7	72.9
Case 68	Low Ind	Low	20	18.9	66.0	22.8	73.0
Case 13	Slot	Low	15	20.7	69.3	22.8	73.0
Case 14	Low Ind	Ceiling	15	20.7	69.3	22.8	73.0
Case 16	Radial	Ceiling	15	18.8	65.8	22.9	73.1
Case 70	Slot	High x4 / Low x4	15	18.8	65.8	22.9	73.2
Case 32	Slot	Low	15	17.5	63.5	22.9	73.2
Case 12	Slot	Ceiling	15	20.7	69.3	22.9	73.2
Case 71	Low Ind	High x4 / Low x4	15	18.8	65.8	23.0	73.3
Case 57	Radial	Low	15	18.8	65.8	23.0	73.4
Case 58	Slot	High	15	18.8	65.8	23.1	73.5
Case 79	Radial	2 Door exhausts	15	18.8	65.8	23.1	73.6
Case 61	Low Ind	Low	15	18.8	65.8	23.1	73.6
Case 33	Low Ind	Low	15	17.5	63.5	23.2	73.7
Case 24	Low Ind	Low	15	18.8	65.8	23.2	73.7
Case 80	Slot	2 Door exhausts	15	18.8	65.8	23.2	73.8
Case 10	Radial	Ceiling	15	20.7	69.3	23.2	73.8
Case 15	Low Ind	Low	15	20.7	69.3	23.2	73.8
Case 28	Low Ind	Low	10	16.8	62.2	23.3	74.0
Case 03	Radial	Low	15	18.8	65.8	23.4	74.0
Case 81	Low Ind	2 Door exhausts	15	18.8	65.8	23.4	74.1
Case 06	Slot	Low	15	18.8	65.8	23.4	74.2
Case 88	Slot	Low	15	19.2	66.6	23.5	74.4
Case 09	Low Ind	Low	15	18.8	65.8	23.6	74.5
Case 30	Low Ind	Low	20	19.8	67.6	23.6	74.6
Case 89	Low Ind	Low	15	19.2	66.6	23.7	74.6

Table 3.09 Ranking of Cases with respect to Room Relative Humidity

Case Name	Supply Diffuser Type	Exhaust Location and Number	Supply ACH	Supply Temperature (°C)	Supply Temperature (°F)	Room RH (percent)
Case 89	Low Ind	Low	15	19.2	66.6	47.1
Case 88	Slot	Low	15	19.2	66.6	48.1
Case 30	Low Ind	Low	20	19.8	67.6	48.2
Case 09	Low Ind	Low	15	18.8	65.8	48.4
Case 87	Radial	Low	15	19.2	66.6	48.4
Case 81	Low Ind	2 Door exhausts	15	18.8	65.8	48.7
Case 06	Slot	Low	15	18.8	65.8	49.2
Case 28	Low Ind	Low	10	16.8	62.2	49.5
Case 03	Radial	Low	15	18.8	65.8	49.7
Case 24	Low Ind	Low	15	18.8	65.8	49.8
Case 80	Slot	2 Door exhausts	15	18.8	65.8	49.8
Case 61	Low Ind	Low	15	18.8	65.8	49.8
Case 79	Radial	2 Door exhausts	15	18.8	65.8	50.3
Case 32	Slot	Low	15	17.5	63.5	50.5
Case 58	Slot	High	15	18.8	65.8	50.6
Case 33	Low Ind	Low	15	17.5	63.5	50.7
Case 23	Slot	Low	15	18.8	65.8	50.7
Case 57	Radial	Low	15	18.8	65.8	50.7
Case 71	Low Ind	High x4 / Low x4	15	18.8	65.8	51.2
Case 70	Slot	High x4 / Low x4	15	18.8	65.8	51.4
Case 11	Radial	Low	15	20.7	69.3	52.0
Case 69	Radial	High x4 / Low x4	15	18.8	65.8	52.2
Case 31	Radial	Low	15	17.5	63.5	52.3
Case 15	Low Ind	Low	15	20.7	69.3	52.3
Case 84	Low Ind	2 Door exhausts	15	17.5	63.5	52.3
Case 22	Radial	Low	15	18.8	65.8	52.3
Case 12	Slot	Ceiling	15	20.7	69.3	52.3
Case 73	Slot	High x4 / Low x2	15	18.8	65.8	52.6
Case 83	Slot	2 Door exhausts	15	17.5	63.5	52.6
Case 68	Low Ind	Low	20	18.9	66.0	52.7
Case 14	Low Ind	Ceiling	15	20.7	69.3	52.7
Case 74	Low Ind	High x4 / Low x2	15	18.8	65.8	52.7
Case 75	Radial	Ceiling/Low 50/50	15	18.8	65.8	52.7
Case 82	Radial	2 Door exhausts	15	18.8	65.8	52.8
Case 72	Radial	High x4 / Low x2	15	18.8	65.8	52.8
Case 64	Low Ind	Low	20	18.9	66.0	52.9
Case 86	Slot	Low	15	17.5	63.5	53.1
Case 10	Radial	Ceiling	15	20.7	69.3	53.1
Case 29	Low Ind	Low	5	11	51.8	53.2
Case 13	Slot	Low	15	20.7	69.3	53.5
Case 38	Slot	Ceiling/Low 50/50	15	18.8	65.8	53.9
Case 39	Low Ind	Ceiling/Low 50/50	15	18.8	65.8	54.0
Case 37	Radial	Ceiling/Low 50/50	15	18.8	65.8	54.2
Case 02	Radial	High	15	18.8	65.8	54.3
Case 40	Radial	Ceiling x4	15	18.8	65.8	54.4
Case 65	Low Ind	Low	15	17.5	63.5	54.4
Case 48	Radial	Ceiling	15	18.8	65.8	54.5
Case 49	Radial	Ceiling	15	18.8	65.8	54.6
Case 05	Slot	High	15	18.8	65.8	54.6
Case 41	Slot	Ceiling x4	15	18.8	65.8	54.6
Case 85	Radial	Low	15	17.5	63.5	54.7

Case Name	Supply Diffuser Type	Exhaust Location and Number	Supply ACH	Supply Temperature (°C)	Supply Temperature (°F)	Room RH (percent)
Case 20	Slot	Ceiling	15	18.8	65.8	54.8
Case 42	Low Ind	Ceiling x4	15	18.8	65.8	54.8
Case 51	Radial	Ceiling	15	18.8	65.8	54.8
Case 50	Radial	Ceiling	15	18.8	65.8	54.9
Case 91	Slot	Ceiling	15	18.8	65.8	55.0
Case 08	Low Ind	High	15	18.8	65.8	55.0
Case 26	Slot	Ceiling	15	18.8	65.8	55.0
Case 59	Slot	Low	15	18.8	65.8	55.0
Case 52	Radial	Ceiling	15	18.8	65.8	55.0
Case 92	Low Ind	Ceiling	15	18.8	65.8	55.0
Case 78	Low Ind	Ceiling	15	18.8	65.8	55.1
Case 04	Slot	Ceiling	15	18.8	65.8	55.1
Case 77	Slot	Ceiling	15	18.8	65.8	55.2
Case 44	Radial (rot 90°)	Ceiling	15	18.8	65.8	55.2
Case 76	Radial	Ceiling	15	18.8	65.8	55.2
Case 21	Low Ind	Ceiling	15	18.8	65.8	55.2
Case 90	Radial	Ceiling	15	18.8	65.8	55.4
Basecase	Radial	Ceiling	15	18.8	65.8	55.4
Case 56	Radial	High	15	18.8	65.8	55.5
Case 47	Radial	Ceiling	15	18.8	65.8	55.5
Case 27	Low Ind	Ceiling	15	18.8	65.8	55.5
Case 25	Radial	Ceiling	15	18.8	65.8	55.6
Case 45	Radial	Ceiling	15	18.8	65.8	55.6
Case 60	Low Ind	High	15	18.8	65.8	55.6
Case 43	Low Ind (rot 90°)	Ceiling	15	18.8	65.8	55.8
Case 95	Low Ind	Ceiling	15	17.5	63.5	55.9
Case 46	Radial	Ceiling	15	18.8	65.8	55.9
Case 19	Radial	Ceiling	15	18.8	65.8	55.9
Case 93	Radial	Ceiling	15	17.5	63.5	55.9
Case 17	Slot	Ceiling	15	18.8	65.8	56.0
Case 18	Low Ind	Ceiling	15	18.8	65.8	56.0
Case 16	Radial	Ceiling	15	18.8	65.8	56.2
Case 94	Slot	Ceiling	15	17.5	63.5	56.3
Case 07	Low Ind	Ceiling	15	18.8	65.8	56.7
Case 63	Low Ind	Low	10	14.8	58.6	56.8
Case 98	Low ind	Ceiling	15	17.5	63.5	56.9
Case 96	Radial	Ceiling	15	17.5	63.5	57.0
Case 97	Slot	Ceiling	15	17.5	63.5	57.0
Case 67	Low Ind	Low	10	14.8	58.6	57.2
Case 35	Slot	Ceiling	15	17.5	63.5	57.4
Case 55	Low Ind	Ceiling	15	18.8	65.8	57.4
Case 54	Slot	Ceiling	15	18.8	65.8	57.4
Case 53	Radial	Ceiling	15	18.8	65.8	57.5
Case 34	Radial	Ceiling	15	17.5	63.5	57.5
Case 36	Low Ind	Ceiling	15	17.5	63.5	57.7
Case 62	Low Ind	Low	5	6.6	43.9	62.6
Case 66	Low Ind	Low	5	6.6	43.9	64.4

Table 3.10 Ranking of Cases with respect to Cage Relative Humidity

Case Name	Supply Diffuser Type	Exhaust Location and Number	Supply ACH	Supply Temperature (°C)	Supply Temperature (°F)	Cage RH (percent)
Case 62	Low Ind	Low	5	6.6	43.9	52.8
Case 66	Low Ind	Low	5	6.6	43.9	53.0
Case 84	Low Ind	2 Door exhausts	15	17.5	63.5	53.0
Case 29	Low Ind	Low	5	11	51.8	55.8
Case 87	Radial	Low	15	19.2	66.6	56.3
Case 64	Low Ind	Low	20	18.9	66.0	56.5
Case 23	Slot	Low	15	18.8	65.8	56.9
Case 69	Radial	High x4 / Low x4	15	18.8	65.8	57.1
Case 68	Low Ind	Low	20	18.9	66.0	57.5
Case 32	Slot	Low	15	17.5	63.5	57.5
Case 57	Radial	Low	15	18.8	65.8	58.3
Case 79	Radial	2 Door exhausts	15	18.8	65.8	58.6
Case 33	Low Ind	Low	15	17.5	63.5	58.7
Case 24	Low Ind	Low	15	18.8	65.8	58.7
Case 80	Slot	2 Door exhausts	15	18.8	65.8	59.1
Case 28	Low Ind	Low	10	16.8	62.2	59.1
Case 03	Radial	Low	15	18.8	65.8	60.2
Case 81	Low Ind	2 Door exhausts	15	18.8	65.8	60.2
Case 06	Slot	Low	15	18.8	65.8	60.2
Case 88	Slot	Low	15	19.2	66.6	60.4
Case 09	Low Ind	Low	15	18.8	65.8	60.6
Case 30	Low Ind	Low	20	19.8	67.6	60.9
Case 89	Low Ind	Low	15	19.2	66.6	60.9
Case 22	Radial	Low	15	18.8	65.8	61.1
Case 31	Radial	Low	15	17.5	63.5	61.4
Case 58	Slot	High	15	18.8	65.8	61.4
Case 61	Low Ind	Low	15	18.8	65.8	61.6
Case 71	Low Ind	High x4 / Low x4	15	18.8	65.8	61.6
Case 10	Radial	Ceiling	15	20.7	69.3	61.7
Case 15	Low Ind	Low	15	20.7	69.3	61.7
Case 70	Slot	High x4 / Low x4	15	18.8	65.8	61.8
Case 82	Radial	2 Door exhausts	15	18.8	65.8	61.9
Case 72	Radial	High x4 / Low x2	15	18.8	65.8	61.9
Case 86	Slot	Low	15	17.5	63.5	62.0
Case 02	Radial	High	15	18.8	65.8	62.0
Case 41	Slot	Ceiling x4	15	18.8	65.8	62.3
Case 74	Low Ind	High x4 / Low x2	15	18.8	65.8	62.3
Case 37	Radial	Ceiling/Low 50/50	15	18.8	65.8	62.4
Case 38	Slot	Ceiling/Low 50/50	15	18.8	65.8	62.4
Case 05	Slot	High	15	18.8	65.8	62.5
Case 20	Slot	Ceiling	15	18.8	65.8	62.6
Case 65	Low Ind	Low	15	17.5	63.5	62.7
Case 04	Slot	Ceiling	15	18.8	65.8	62.7
Case 42	Low Ind	Ceiling x4	15	18.8	65.8	62.8
Case 92	Low Ind	Ceiling	15	18.8	65.8	62.8
Case 85	Radial	Low	15	17.5	63.5	62.8
Case 39	Low Ind	Ceiling/Low 50/50	15	18.8	65.8	62.9
Case 73	Slot	High x4 / Low x2	15	18.8	65.8	62.9
Case 90	Radial	Ceiling	15	18.8	65.8	63.3
Case 91	Slot	Ceiling	15	18.8	65.8	63.4
Case 11	Radial	Low	15	20.7	69.3	63.6

Case Name	Supply Diffuser Type	Exhaust Location and Number	Supply ACH	Supply Temperature (°C)	Supply Temperature (°F)	Cage RH (percent)
Case 12	Slot	Ceiling	15	20.7	69.3	63.6
Case 50	Radial	Ceiling	15	18.8	65.8	63.7
Case 18	Low Ind	Ceiling	15	18.8	65.8	63.8
Case 08	Low Ind	High	15	18.8	65.8	63.8
Case 17	Slot	Ceiling	15	18.8	65.8	63.9
Case 16	Radial	Ceiling	15	18.8	65.8	64.0
Case 76	Radial	Ceiling	15	18.8	65.8	64.1
Case 21	Low Ind	Ceiling	15	18.8	65.8	64.1
Case 95	Low Ind	Ceiling	15	17.5	63.5	64.1
Case 77	Slot	Ceiling	15	18.8	65.8	64.2
Case 14	Low Ind	Ceiling	15	20.7	69.3	64.2
Case 97	Slot	Ceiling	15	17.5	63.5	64.2
Case 94	Slot	Ceiling	15	17.5	63.5	64.4
Case 56	Radial	High	15	18.8	65.8	64.4
Case 43	Low Ind (rot 90°)	Ceiling	15	18.8	65.8	64.6
Case 19	Radial	Ceiling	15	18.8	65.8	64.6
Case 78	Low Ind	Ceiling	15	18.8	65.8	64.7
Case 52	Radial	Ceiling	15	18.8	65.8	64.8
Case 40	Radial	Ceiling x4	15	18.8	65.8	64.8
Case 45	Radial	Ceiling	15	18.8	65.8	64.9
Case 75	Radial	Ceiling/Low 50/50	15	18.8	65.8	64.9
Case 63	Low Ind	Low	10	14.8	58.6	64.9
Case 93	Radial	Ceiling	15	17.5	63.5	65.0
Case 47	Radial	Ceiling	15	18.8	65.8	65.1
Case 49	Radial	Ceiling	15	18.8	65.8	65.2
Case 46	Radial	Ceiling	15	18.8	65.8	65.2
Case 51	Radial	Ceiling	15	18.8	65.8	65.3
Case 35	Slot	Ceiling	15	17.5	63.5	65.5
Case 67	Low Ind	Low	10	14.8	58.6	65.8
Case 98	Low ind	Ceiling	15	17.5	63.5	65.8
Case 96	Radial	Ceiling	15	17.5	63.5	65.8
Case 54	Slot	Ceiling	15	18.8	65.8	66.0
Case 44	Radial (rot 90°)	Ceiling	15	18.8	65.8	66.0
Case 48	Radial	Ceiling	15	18.8	65.8	66.1
Case 07	Low Ind	Ceiling	15	18.8	65.8	66.4
Case 13	Slot	Low	15	20.7	69.3	66.5
Case 36	Low Ind	Ceiling	15	17.5	63.5	66.5
Basecase	Radial	Ceiling	15	18.8	65.8	66.8
Case 83	Slot	2 Door exhausts	15	17.5	63.5	66.8
Case 59	Slot	Low	15	18.8	65.8	66.9
Case 34	Radial	Ceiling	15	17.5	63.5	67.2
Case 55	Low Ind	Ceiling	15	18.8	65.8	67.8
Case 53	Radial	Ceiling	15	18.8	65.8	68.8
Case 60	Low Ind	High	15	18.8	65.8	69.1
Case 25	Radial	Ceiling	15	18.8	65.8	73.0
Case 27	Low Ind	Ceiling	15	18.8	65.8	74.8
Case 26	Slot	Ceiling	15	18.8	65.8	81.2

Table 3.11 Ranking of Cases with respect to Room CO_2

Case Name	Supply Diffuser Type	Exhaust Location and Number	Supply ACH	Supply Temperature (°C)	Supply Temperature (°F)	Room CO_2 (ppm)
Case 59	Slot	Low	15	18.8	65.8	15
Case 12	Slot	Ceiling	15	20.7	69.3	17
Case 40	Radial	Ceiling x4	15	18.8	65.8	21
Case 70	Slot	High x4 / Low x4	15	18.8	65.8	24
Case 10	Radial	Ceiling	15	20.7	69.3	29
Case 26	Slot	Ceiling	15	18.8	65.8	35
Basecase	Radial	Ceiling	15	18.8	65.8	36
Case 13	Slot	Low	15	20.7	69.3	37
Case 16	Radial	Ceiling	15	18.8	65.8	37
Case 73	Slot	High x4 / Low x2	15	18.8	65.8	37
Case 47	Radial	Ceiling	15	18.8	65.8	40
Case 92	Low Ind	Ceiling	15	18.8	65.8	41
Case 46	Radial	Ceiling	15	18.8	65.8	43
Case 87	Radial	Low	15	19.2	66.6	45
Case 11	Radial	Low	15	20.7	69.3	48
Case 74	Low Ind	High x4 / Low x2	15	18.8	65.8	48
Case 75	Radial	Ceiling/Low 50/50	15	18.8	65.8	48
Case 88	Slot	Low	15	19.2	66.6	48
Case 15	Low Ind	Low	15	20.7	69.3	48
Case 72	Radial	High x4 / Low x2	15	18.8	65.8	48
Case 05	Slot	High	15	18.8	65.8	49
Case 77	Slot	Ceiling	15	18.8	65.8	50
Case 41	Slot	Ceiling x4	15	18.8	65.8	51
Case 69	Radial	High x4 / Low x4	15	18.8	65.8	51
Case 71	Low Ind	High x4 / Low x4	15	18.8	65.8	51
Case 49	Radial	Ceiling	15	18.8	65.8	52
Case 14	Low Ind	Ceiling	15	20.7	69.3	52
Case 45	Radial	Ceiling	15	18.8	65.8	52
Case 50	Radial	Ceiling	15	18.8	65.8	55
Case 76	Radial	Ceiling	15	18.8	65.8	55
Case 78	Low Ind	Ceiling	15	18.8	65.8	55
Case 60	Low Ind	High	15	18.8	65.8	57
Case 07	Low Ind	Ceiling	15	18.8	65.8	57
Case 55	Low Ind	Ceiling	15	18.8	65.8	57
Case 91	Slot	Ceiling	15	18.8	65.8	57
Case 57	Radial	Low	15	18.8	65.8	57
Case 53	Radial	Ceiling	15	18.8	65.8	58
Case 37	Radial	Ceiling/Low 50/50	15	18.8	65.8	59
Case 19	Radial	Ceiling	15	18.8	65.8	59
Case 54	Slot	Ceiling	15	18.8	65.8	60
Case 25	Radial	Ceiling	15	18.8	65.8	60
Case 22	Radial	Low	15	18.8	65.8	61
Case 27	Low Ind	Ceiling	15	18.8	65.8	61
Case 21	Low Ind	Ceiling	15	18.8	65.8	62
Case 04	Slot	Ceiling	15	18.8	65.8	62
Case 89	Low Ind	Low	15	19.2	66.6	62
Case 38	Slot	Ceiling/Low 50/50	15	18.8	65.8	62
Case 23	Slot	Low	15	18.8	65.8	63
Case 42	Low Ind	Ceiling x4	15	18.8	65.8	63
Case 30	Low Ind	Low	20	19.8	67.6	64
Case 08	Low Ind	High	15	18.8	65.8	64

Case Name	Supply Diffuser Type	Exhaust Location and Number	Supply ACH	Supply Temperature (°C)	Supply Temperature (°F)	Room CO_2 (ppm)
Case 03	Radial	Low	15	18.8	65.8	64
Case 48	Radial	Ceiling	15	18.8	65.8	65
Case 02	Radial	High	15	18.8	65.8	65
Case 52	Radial	Ceiling	15	18.8	65.8	65
Case 43	Low Ind (rot 90°)	Ceiling	15	18.8	65.8	65
Case 51	Radial	Ceiling	15	18.8	65.8	67
Case 58	Slot	High	15	18.8	65.8	68
Case 61	Low Ind	Low	15	18.8	65.8	69
Case 56	Radial	High	15	18.8	65.8	69
Case 95	Low Ind	Ceiling	15	17.5	63.5	69
Case 39	Low Ind	Ceiling/Low 50/50	15	18.8	65.8	71
Case 06	Slot	Low	15	18.8	65.8	72
Case 90	Radial	Ceiling	15	18.8	65.8	72
Case 44	Radial (rot 90°)	Ceiling	15	18.8	65.8	74
Case 20	Slot	Ceiling	15	18.8	65.8	75
Case 17	Slot	Ceiling	15	18.8	65.8	78
Case 18	Low Ind	Ceiling	15	18.8	65.8	79
Case 79	Radial	2 Door exhausts	15	18.8	65.8	81
Case 24	Low Ind	Low	15	18.8	65.8	81
Case 98	Low ind	Ceiling	15	17.5	63.5	83
Case 93	Radial	Ceiling	15	17.5	63.5	86
Case 09	Low Ind	Low	15	18.8	65.8	88
Case 81	Low Ind	2 Door exhausts	15	18.8	65.8	89
Case 80	Slot	2 Door exhausts	15	18.8	65.8	90
Case 68	Low Ind	Low	20	18.9	66.0	93
Case 64	Low Ind	Low	20	18.9	66.0	93
Case 96	Radial	Ceiling	15	17.5	63.5	100
Case 31	Radial	Low	15	17.5	63.5	107
Case 97	Slot	Ceiling	15	17.5	63.5	111
Case 28	Low Ind	Low	10	16.8	62.2	113
Case 82	Radial	2 Door exhausts	15	18.8	65.8	116
Case 94	Slot	Ceiling	15	17.5	63.5	117
Case 35	Slot	Ceiling	15	17.5	63.5	122
Case 86	Slot	Low	15	17.5	63.5	124
Case 32	Slot	Low	15	17.5	63.5	125
Case 85	Radial	Low	15	17.5	63.5	132
Case 65	Low Ind	Low	15	17.5	63.5	133
Case 36	Low Ind	Ceiling	15	17.5	63.5	134
Case 34	Radial	Ceiling	15	17.5	63.5	136
Case 29	Low Ind	Low	5	11	51.8	140
Case 33	Low Ind	Low	15	17.5	63.5	143
Case 84	Low Ind	2 Door exhausts	15	17.5	63.5	152
Case 83	Slot	2 Door exhausts	15	17.5	63.5	167
Case 67	Low Ind	Low	10	14.8	58.6	201
Case 63	Low Ind	Low	10	14.8	58.6	215
Case 66	Low Ind	Low	5	6.6	43.9	318
Case 62	Low Ind	Low	5	6.6	43.9	342

Table 3.12 Ranking of Cases with respect to Cage CO_2

Case Name	Supply Diffuser Type	Exhaust Location and Number	Supply ACH	Supply Temperature (°C)	Supply Temperature (°F)	Cage CO_2 (ppm)
Case 87	Radial	Low	15	19.2	66.6	1391
Case 88	Slot	Low	15	19.2	66.6	1550
Case 03	Radial	Low	15	18.8	65.8	1568
Case 92	Low Ind	Ceiling	15	18.8	65.8	1631
Case 89	Low Ind	Low	15	19.2	66.6	1636
Case 79	Radial	2 Door exhausts	15	18.8	65.8	1647
Case 23	Slot	Low	15	18.8	65.8	1652
Case 06	Slot	Low	15	18.8	65.8	1652
Case 20	Slot	Ceiling	15	18.8	65.8	1656
Case 52	Radial	Ceiling	15	18.8	65.8	1665
Case 22	Radial	Low	15	18.8	65.8	1665
Case 82	Radial	2 Door exhausts	15	18.8	65.8	1667
Case 30	Low Ind	Low	20	19.8	67.6	1667
Case 90	Radial	Ceiling	15	18.8	65.8	1673
Case 41	Slot	Ceiling x4	15	18.8	65.8	1690
Case 02	Radial	High	15	18.8	65.8	1703
Case 80	Slot	2 Door exhausts	15	18.8	65.8	1707
Case 04	Slot	Ceiling	15	18.8	65.8	1709
Case 91	Slot	Ceiling	15	18.8	65.8	1709
Case 37	Radial	Ceiling/Low 50/50	15	18.8	65.8	1715
Case 97	Slot	Ceiling	15	17.5	63.5	1725
Case 09	Low Ind	Low	15	18.8	65.8	1725
Case 19	Radial	Ceiling	15	18.8	65.8	1725
Case 42	Low Ind	Ceiling x4	15	18.8	65.8	1728
Case 81	Low Ind	2 Door exhausts	15	18.8	65.8	1741
Case 05	Slot	High	15	18.8	65.8	1742
Case 32	Slot	Low	15	17.5	63.5	1747
Case 28	Low Ind	Low	10	16.8	62.2	1749
Case 69	Radial	High x4 / Low x4	15	18.8	65.8	1750
Case 83	Slot	2 Door exhausts	15	17.5	63.5	1756
Case 94	Slot	Ceiling	15	17.5	63.5	1757
Case 35	Slot	Ceiling	15	17.5	63.5	1761
Case 29	Low Ind	Low	5	11	51.8	1764
Case 38	Slot	Ceiling/Low 50/50	15	18.8	65.8	1776
Case 72	Radial	High x4 / Low x2	15	18.8	65.8	1790
Case 18	Low Ind	Ceiling	15	18.8	65.8	1791
Case 64	Low Ind	Low	20	18.9	66.0	1808
Case 21	Low Ind	Ceiling	15	18.8	65.8	1808
Case 17	Slot	Ceiling	15	18.8	65.8	1815
Case 95	Low Ind	Ceiling	15	17.5	63.5	1822
Case 93	Radial	Ceiling	15	17.5	63.5	1822
Case 68	Low Ind	Low	20	18.9	66.0	1838
Case 75	Radial	Ceiling/Low 50/50	15	18.8	65.8	1839
Case 50	Radial	Ceiling	15	18.8	65.8	1840
Case 39	Low Ind	Ceiling/Low 50/50	15	18.8	65.8	1848
Case 84	Low Ind	2 Door exhausts	15	17.5	63.5	1853
Case 57	Radial	Low	15	18.8	65.8	1855
Case 43	Low Ind (rot 90°)	Ceiling	15	18.8	65.8	1855
Case 76	Radial	Ceiling	15	18.8	65.8	1857
Case 54	Slot	Ceiling	15	18.8	65.8	1869
Case 08	Low Ind	High	15	18.8	65.8	1871

Case Name	Supply Diffuser Type	Exhaust Location and Number	Supply ACH	Supply Temperature (°C)	Supply Temperature (°F)	Cage CO_2 (ppm)
Case 36	Low Ind	Ceiling	15	17.5	63.5	1878
Case 77	Slot	Ceiling	15	18.8	65.8	1881
Case 24	Low Ind	Low	15	18.8	65.8	1883
Case 74	Low Ind	High x4 / Low x2	15	18.8	65.8	1884
Case 56	Radial	High	15	18.8	65.8	1886
Case 34	Radial	Ceiling	15	17.5	63.5	1896
Case 86	Slot	Low	15	17.5	63.5	1917
Case 78	Low Ind	Ceiling	15	18.8	65.8	1919
Case 45	Radial	Ceiling	15	18.8	65.8	1929
Case 85	Radial	Low	15	17.5	63.5	1930
Case 31	Radial	Low	15	17.5	63.5	1938
Case 46	Radial	Ceiling	15	18.8	65.8	1943
Case 98	Low ind	Ceiling	15	17.5	63.5	1955
Case 70	Slot	High x4 / Low x4	15	18.8	65.8	1955
Case 96	Radial	Ceiling	15	17.5	63.5	1957
Case 47	Radial	Ceiling	15	18.8	65.8	1961
Case 73	Slot	High x4 / Low x2	15	18.8	65.8	1966
Case 71	Low Ind	High x4 / Low x4	15	18.8	65.8	1968
Case 33	Low Ind	Low	15	17.5	63.5	1974
Case 40	Radial	Ceiling x4	15	18.8	65.8	1975
Case 58	Slot	High	15	18.8	65.8	1990
Case 65	Low Ind	Low	15	17.5	63.5	2002
Case 49	Radial	Ceiling	15	18.8	65.8	2025
Case 55	Low Ind	Ceiling	15	18.8	65.8	2039
Case 61	Low Ind	Low	15	18.8	65.8	2042
Case 51	Radial	Ceiling	15	18.8	65.8	2045
Case 63	Low Ind	Low	10	14.8	58.6	2081
Case 48	Radial	Ceiling	15	18.8	65.8	2099
Case 11	Radial	Low	15	20.7	69.3	2118
Case 44	Radial (rot 90°)	Ceiling	15	18.8	65.8	2118
Case 10	Radial	Ceiling	15	20.7	69.3	2119
Case 15	Low Ind	Low	15	20.7	69.3	2119
Case 67	Low Ind	Low	10	14.8	58.6	2144
Basecase	Radial	Ceiling	15	18.8	65.8	2158
Case 59	Slot	Low	15	18.8	65.8	2161
Case 12	Slot	Ceiling	15	20.7	69.3	2208
Case 53	Radial	Ceiling	15	18.8	65.8	2212
Case 16	Radial	Ceiling	15	18.8	65.8	2213
Case 14	Low Ind	Ceiling	15	20.7	69.3	2215
Case 66	Low Ind	Low	5	6.6	43.9	2318
Case 07	Low Ind	Ceiling	15	18.8	65.8	2321
Case 62	Low Ind	Low	5	6.6	43.9	2325
Case 60	Low Ind	High	15	18.8	65.8	2354
Case 13	Slot	Low	15	20.7	69.3	2491
Case 25	Radial	Ceiling	15	18.8	65.8	3008
Case 27	Low Ind	Ceiling	15	18.8	65.8	3171
Case 26	Slot	Ceiling	15	18.8	65.8	3975

Table 3.13 Ranking of Cases with respect to Room NH_3

Case Name	Supply Diffuser Type	Exhaust Location and Number	Supply ACH	Supply Temperature (°C)	Supply Temperature (°F)	Room NH_3 (day 4) (ppm)
Case 59	Slot	Low	15	18.8	65.8	0.04
Case 12	Slot	Ceiling	15	20.7	69.3	0.04
Case 70	Slot	High x4 / Low x4	15	18.8	65.8	0.06
Case 40	Radial	Ceiling x4	15	18.8	65.8	0.06
Case 10	Radial	Ceiling	15	20.7	69.3	0.07
Case 73	Slot	High x4 / Low x2	15	18.8	65.8	0.09
Case 16	Radial	Ceiling	15	18.8	65.8	0.10
Case 87	Radial	Low	15	19.2	66.6	0.10
Case 92	Low Ind	Ceiling	15	18.8	65.8	0.10
Basecase	Radial	Ceiling	15	18.8	65.8	0.11
Case 13	Slot	Low	15	20.7	69.3	0.11
Case 88	Slot	Low	15	19.2	66.6	0.11
Case 47	Radial	Ceiling	15	18.8	65.8	0.11
Case 15	Low Ind	Low	15	20.7	69.3	0.11
Case 72	Radial	High x4 / Low x2	15	18.8	65.8	0.11
Case 74	Low Ind	High x4 / Low x2	15	18.8	65.8	0.11
Case 69	Radial	High x4 / Low x4	15	18.8	65.8	0.12
Case 46	Radial	Ceiling	15	18.8	65.8	0.12
Case 71	Low Ind	High x4 / Low x4	15	18.8	65.8	0.12
Case 05	Slot	High	15	18.8	65.8	0.12
Case 41	Slot	Ceiling x4	15	18.8	65.8	0.12
Case 11	Radial	Low	15	20.7	69.3	0.12
Case 57	Radial	Low	15	18.8	65.8	0.13
Case 75	Radial	Ceiling/Low 50/50	15	18.8	65.8	0.13
Case 77	Slot	Ceiling	15	18.8	65.8	0.13
Case 14	Low Ind	Ceiling	15	20.7	69.3	0.14
Case 22	Radial	Low	15	18.8	65.8	0.14
Case 89	Low Ind	Low	15	19.2	66.6	0.14
Case 50	Radial	Ceiling	15	18.8	65.8	0.14
Case 37	Radial	Ceiling/Low 50/50	15	18.8	65.8	0.14
Case 23	Slot	Low	15	18.8	65.8	0.14
Case 45	Radial	Ceiling	15	18.8	65.8	0.14
Case 49	Radial	Ceiling	15	18.8	65.8	0.14
Case 30	Low Ind	Low	20	19.8	67.6	0.14
Case 03	Radial	Low	15	18.8	65.8	0.14
Case 76	Radial	Ceiling	15	18.8	65.8	0.14
Case 91	Slot	Ceiling	15	18.8	65.8	0.14
Case 78	Low Ind	Ceiling	15	18.8	65.8	0.15
Case 38	Slot	Ceiling/Low 50/50	15	18.8	65.8	0.15
Case 04	Slot	Ceiling	15	18.8	65.8	0.15
Case 02	Radial	High	15	18.8	65.8	0.15
Case 42	Low Ind	Ceiling x4	15	18.8	65.8	0.16
Case 58	Slot	High	15	18.8	65.8	0.16
Case 19	Radial	Ceiling	15	18.8	65.8	0.16
Case 61	Low Ind	Low	15	18.8	65.8	0.16
Case 26	Slot	Ceiling	15	18.8	65.8	0.16
Case 06	Slot	Low	15	18.8	65.8	0.16
Case 21	Low Ind	Ceiling	15	18.8	65.8	0.16
Case 07	Low Ind	Ceiling	15	18.8	65.8	0.16
Case 08	Low Ind	High	15	18.8	65.8	0.16
Case 54	Slot	Ceiling	15	18.8	65.8	0.17

Case Name	Supply Diffuser Type	Exhaust Location and Number	Supply ACH	Supply Temperature (°C)	Supply Temperature (°F)	Room NH_3 (day 4) (ppm)
Case 43	Low Ind (rot 90°)	Ceiling	15	18.8	65.8	0.17
Case 55	Low Ind	Ceiling	15	18.8	65.8	0.17
Case 52	Radial	Ceiling	15	18.8	65.8	0.18
Case 39	Low Ind	Ceiling/Low 50/50	15	18.8	65.8	0.18
Case 90	Radial	Ceiling	15	18.8	65.8	0.18
Case 60	Low Ind	High	15	18.8	65.8	0.18
Case 95	Low Ind	Ceiling	15	17.5	63.5	0.18
Case 20	Slot	Ceiling	15	18.8	65.8	0.18
Case 79	Radial	2 Door exhausts	15	18.8	65.8	0.18
Case 24	Low Ind	Low	15	18.8	65.8	0.18
Case 56	Radial	High	15	18.8	65.8	0.18
Case 48	Radial	Ceiling	15	18.8	65.8	0.18
Case 51	Radial	Ceiling	15	18.8	65.8	0.18
Case 53	Radial	Ceiling	15	18.8	65.8	0.18
Case 09	Low Ind	Low	15	18.8	65.8	0.20
Case 81	Low Ind	2 Door exhausts	15	18.8	65.8	0.20
Case 17	Slot	Ceiling	15	18.8	65.8	0.20
Case 80	Slot	2 Door exhausts	15	18.8	65.8	0.20
Case 18	Low Ind	Ceiling	15	18.8	65.8	0.20
Case 68	Low Ind	Low	20	18.9	66.0	0.21
Case 64	Low Ind	Low	20	18.9	66.0	0.21
Case 44	Radial (rot 90°)	Ceiling	15	18.8	65.8	0.21
Case 25	Radial	Ceiling	15	18.8	65.8	0.22
Case 98	Low ind	Ceiling	15	17.5	63.5	0.23
Case 93	Radial	Ceiling	15	17.5	63.5	0.24
Case 27	Low Ind	Ceiling	15	18.8	65.8	0.24
Case 31	Radial	Low	15	17.5	63.5	0.24
Case 28	Low Ind	Low	10	16.8	62.2	0.25
Case 82	Radial	2 Door exhausts	15	18.8	65.8	0.27
Case 32	Slot	Low	15	17.5	63.5	0.28
Case 96	Radial	Ceiling	15	17.5	63.5	0.28
Case 97	Slot	Ceiling	15	17.5	63.5	0.29
Case 86	Slot	Low	15	17.5	63.5	0.29
Case 94	Slot	Ceiling	15	17.5	63.5	0.31
Case 29	Low Ind	Low	5	11	51.8	0.32
Case 33	Low Ind	Low	15	17.5	63.5	0.32
Case 85	Radial	Low	15	17.5	63.5	0.33
Case 65	Low Ind	Low	15	17.5	63.5	0.33
Case 35	Slot	Ceiling	15	17.5	63.5	0.34
Case 84	Low Ind	2 Door exhausts	15	17.5	63.5	0.34
Case 36	Low Ind	Ceiling	15	17.5	63.5	0.39
Case 34	Radial	Ceiling	15	17.5	63.5	0.41
Case 83	Slot	2 Door exhausts	15	17.5	63.5	0.49
Case 67	Low Ind	Low	10	14.8	58.6	0.57
Case 63	Low Ind	Low	10	14.8	58.6	0.58
Case 66	Low Ind	Low	5	6.6	43.9	0.72
Case 62	Low Ind	Low	5	6.6	43.9	0.77

Table 3.14 Ranking of Cases with respect to Cage NH_3 (Day 4)

Case Name	Supply Diffuser Type	Exhaust Location and Number	Supply ACH	Supply Temperature (°C)	Supply Temperature (°F)	Cage NH_3 (day 4) (ppm)
Case 87	Radial	Low	15	19.2	66.6	3.13
Case 88	Slot	Low	15	19.2	66.6	3.49
Case 03	Radial	Low	15	18.8	65.8	3.53
Case 89	Low Ind	Low	15	19.2	66.6	3.68
Case 79	Radial	2 Door exhausts	15	18.8	65.8	3.70
Case 23	Slot	Low	15	18.8	65.8	3.71
Case 06	Slot	Low	15	18.8	65.8	3.72
Case 30	Low Ind	Low	20	19.8	67.6	3.75
Case 22	Radial	Low	15	18.8	65.8	3.77
Case 80	Slot	2 Door exhausts	15	18.8	65.8	3.84
Case 09	Low Ind	Low	15	18.8	65.8	3.88
Case 81	Low Ind	2 Door exhausts	15	18.8	65.8	3.92
Case 82	Radial	2 Door exhausts	15	18.8	65.8	3.92
Case 32	Slot	Low	15	17.5	63.5	3.93
Case 28	Low Ind	Low	10	16.8	62.2	3.93
Case 69	Radial	High x4 / Low x4	15	18.8	65.8	3.94
Case 29	Low Ind	Low	5	11	51.8	3.97
Case 92	Low Ind	Ceiling	15	18.8	65.8	4.02
Case 02	Radial	High	15	18.8	65.8	4.03
Case 20	Slot	Ceiling	15	18.8	65.8	4.04
Case 41	Slot	Ceiling x4	15	18.8	65.8	4.06
Case 64	Low Ind	Low	20	18.9	66.0	4.07
Case 37	Radial	Ceiling/Low 50/50	15	18.8	65.8	4.13
Case 68	Low Ind	Low	20	18.9	66.0	4.13
Case 84	Low Ind	2 Door exhausts	15	17.5	63.5	4.17
Case 57	Radial	Low	15	18.8	65.8	4.17
Case 04	Slot	Ceiling	15	18.8	65.8	4.18
Case 72	Radial	High x4 / Low x2	15	18.8	65.8	4.22
Case 90	Radial	Ceiling	15	18.8	65.8	4.22
Case 05	Slot	High	15	18.8	65.8	4.23
Case 24	Low Ind	Low	15	18.8	65.8	4.24
Case 42	Low Ind	Ceiling x4	15	18.8	65.8	4.25
Case 38	Slot	Ceiling/Low 50/50	15	18.8	65.8	4.28
Case 91	Slot	Ceiling	15	18.8	65.8	4.33
Case 33	Low Ind	Low	15	17.5	63.5	4.44
Case 31	Radial	Low	15	17.5	63.5	4.45
Case 52	Radial	Ceiling	15	18.8	65.8	4.49
Case 74	Low Ind	High x4 / Low x2	15	18.8	65.8	4.53
Case 97	Slot	Ceiling	15	17.5	63.5	4.54
Case 86	Slot	Low	15	17.5	63.5	4.54
Case 71	Low Ind	High x4 / Low x4	15	18.8	65.8	4.56
Case 58	Slot	High	15	18.8	65.8	4.58
Case 39	Low Ind	Ceiling/Low 50/50	15	18.8	65.8	4.58
Case 70	Slot	High x4 / Low x4	15	18.8	65.8	4.58
Case 19	Radial	Ceiling	15	18.8	65.8	4.61
Case 18	Low Ind	Ceiling	15	18.8	65.8	4.62
Case 94	Slot	Ceiling	15	17.5	63.5	4.66
Case 17	Slot	Ceiling	15	18.8	65.8	4.71
Case 61	Low Ind	Low	15	18.8	65.8	4.73
Case 21	Low Ind	Ceiling	15	18.8	65.8	4.73
Case 50	Radial	Ceiling	15	18.8	65.8	4.73

Case Name	Supply Diffuser Type	Exhaust Location and Number	Supply ACH	Supply Temperature (°C)	Supply Temperature (°F)	Cage NH_3 (day 4) (ppm)
Case 85	Radial	Low	15	17.5	63.5	4.76
Case 95	Low Ind	Ceiling	15	17.5	63.5	4.77
Case 08	Low Ind	High	15	18.8	65.8	4.83
Case 76	Radial	Ceiling	15	18.8	65.8	4.85
Case 73	Slot	High x4 / Low x2	15	18.8	65.8	4.87
Case 65	Low Ind	Low	15	17.5	63.5	4.90
Case 35	Slot	Ceiling	15	17.5	63.5	4.90
Case 77	Slot	Ceiling	15	18.8	65.8	4.94
Case 10	Radial	Ceiling	15	20.7	69.3	4.94
Case 15	Low Ind	Low	15	20.7	69.3	4.94
Case 43	Low Ind (rot 90°)	Ceiling	15	18.8	65.8	4.96
Case 93	Radial	Ceiling	15	17.5	63.5	4.97
Case 75	Radial	Ceiling/Low 50/50	15	18.8	65.8	4.98
Case 56	Radial	High	15	18.8	65.8	5.01
Case 83	Slot	2 Door exhausts	15	17.5	63.5	5.15
Case 78	Low Ind	Ceiling	15	18.8	65.8	5.16
Case 66	Low Ind	Low	5	6.6	43.9	5.21
Case 45	Radial	Ceiling	15	18.8	65.8	5.22
Case 62	Low Ind	Low	5	6.6	43.9	5.23
Case 54	Slot	Ceiling	15	18.8	65.8	5.32
Case 40	Radial	Ceiling x4	15	18.8	65.8	5.33
Case 46	Radial	Ceiling	15	18.8	65.8	5.35
Case 47	Radial	Ceiling	15	18.8	65.8	5.36
Case 11	Radial	Low	15	20.7	69.3	5.42
Case 36	Low Ind	Ceiling	15	17.5	63.5	5.44
Case 98	Low ind	Ceiling	15	17.5	63.5	5.50
Case 96	Radial	Ceiling	15	17.5	63.5	5.51
Case 49	Radial	Ceiling	15	18.8	65.8	5.56
Case 51	Radial	Ceiling	15	18.8	65.8	5.64
Case 63	Low Ind	Low	10	14.8	58.6	5.64
Case 12	Slot	Ceiling	15	20.7	69.3	5.66
Case 34	Radial	Ceiling	15	17.5	63.5	5.66
Case 16	Radial	Ceiling	15	18.8	65.8	5.76
Case 14	Low Ind	Ceiling	15	20.7	69.3	5.82
Case 48	Radial	Ceiling	15	18.8	65.8	5.98
Case 44	Radial (rot 90°)	Ceiling	15	18.8	65.8	6.03
Case 67	Low Ind	Low	10	14.8	58.6	6.03
Case 55	Low Ind	Ceiling	15	18.8	65.8	6.22
Basecase	Radial	Ceiling	15	18.8	65.8	6.33
Case 59	Slot	Low	15	18.8	65.8	6.38
Case 07	Low Ind	Ceiling	15	18.8	65.8	6.71
Case 53	Radial	Ceiling	15	18.8	65.8	7.02
Case 13	Slot	Low	15	20.7	69.3	7.21
Case 60	Low Ind	High	15	18.8	65.8	7.56
Case 25	Radial	Ceiling	15	18.8	65.8	11.05
Case 27	Low Ind	Ceiling	15	18.8	65.8	12.31
Case 26	Slot	Ceiling	15	18.8	65.8	18.42

3.4 Recommendations

There were a total of 101 typical animal room and ventilation configurations analyzed by CFD simulation and subjected to rigorous quantitative post-processing. The analysis focused on CO_2 and NH_3 concentrations in the scientist's breathing zone (4'11''- 5'11'', 1.5m to 1.8m) and in the cages occupied by mice. As stated in section 3.2, the nominal pass/fail limits chosen were 1 ppm NH_3 in the breathing zone and 25 ppm NH_3 in the cage.

The results of the CFD simulations performed in this study show that no particular room layout or ventilation system produces consistently good or bad results. Indeed, often improvements in the room are accompanied by poorer ventilation in the cages. The CO_2 concentration values are representative of any airborne contaminants, whereas the NH_3 concentrations that are related to the CO_2 concentrations also depend on temperature and relative humidity.

- The level of CO_2 concentration in the room breathing zone depends on both the flow rate into the room and the number of cages, and mice present in the room. Doubling the number of cages leads to approximately double the amount of CO_2. Rooms with low stocking density could be operated with lower flow rates;

- Acceptable day 5 NH_3 concentrations are produced by supply flow rates of 0.85cfm (4.01e-4 m^3/s) per 100g body weight of mice (equivalent to 5 ACH for single density racks, 10 ACH for double density racks);

- Acceptable day 6 NH_3 concentrations are produced by supply flow rates of around 1.28cfm (6.04e-4 m^3/s) per 100g body weight of mice (equivalent to 7.5 ACH for single density racks, 15 ACH for double density racks);

- Changing bedding every four to five days will produce acceptable rooms (at supply flow rates of around 0.85 cfm (4.01e-4 m^3/s) per 100g body weight of mice) and acceptable cage environments for the mice;

- Increasing the cage temperature by 3.0 °C (5.4 °F) could extend the period for changing to six or seven days, and can provide a better environment for the mice;

- Ceiling level exhausts often provide poor ventilation for cages, compared with low level exhausts;

- Although increasing the ventilation rate reduces the concentration of contaminants in the occupied zone of the room by increased dilution, the same cannot be said for cage concentrations. In fact, with single cage density, the cage concentrations of NH_3 were seen to rise with ventilation rates increasing from 15 to 20 ACH;

- Higher temperatures in the room and cages reduce the relative humidity, and NH_3 generation and concentrations. Although this can be achieved by low level exhausts (which consistently

appear to produce higher temperatures) it is better achieved by increasing the supply discharge temperature for high level and ceiling exhausts, resulting in less cooling in the room and, therefore, lower running costs.

The experimental measurement of NH_3 generation shows dependency on relative humidity. As relative humidity is dependent on temperature (if the level of moisture in the air is constant), raising the temperature in the room and cages will reduce the levels of NH_3. Further, as indicated in the study by Gordon, Becker and Ali (1997), increasing the cage temperatures above the normal 22.0 to 23.0 °C (72.0 to 74.0 °F) is likely to provide a more comfortable environment for the mice. A recommendation of this study is that the supply discharge temperatures should be increased by 3.0 to 4.0 °C (5.4 to 7.2 °F) to about 23.0 °C (73.4 °F). This will provide room temperatures around 25 °C (77 °F) and cages with a temperature of about 26.0 °C (78.8 °F), though a few individual cages may rise as high as 28.0 °C (82.4 °F).

SECTION IV

EXPERIMENTAL WORK AND VERIFICATION OF CFD METHODOLOGY

SECTION IV: TABLE OF CONTENTS

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4. EXPERIMENTAL WORK AND VERIFICATION OF CFD METHODOLOGY

4.1 Experimental Work

4.1.1 Cage Condition

4.1.1.1 Objective

Several series of experimental scenarios were defined to consider a known mouse cage placed in a wind tunnel. The primary objective of the experimental measurements was to create and measure various airflow s within the mouse cage in such a manner as to lay the ground work for determining the boundary conditions for the computational fluid dynamics (CFD) analysis of the cage. In particular, a series of CFD models were constructed to simulate the cage wind tunnel experiments. The primary reason for the validation of the CFD model of the cage against experimental data were to obtain an appropriate set of boundary conditions to represent the cage in the whole room simulations. The two sets of boundary conditions that are of most concern are those associated with the transfer mechanisms into and out of the cage, namely the side cracks and the top of the cage, that includes the filter media.

4.1.1.2 Experimental Apparatus

The apparatus used in this series of experimental scenarios was kept relatively constant throughout, with the main difference being the representation of the mice within the cage.

The wind tunnel cross section was 0.40 m x 0.50 m (15.75" wide x 20" deep). It was 1.72m (68") long with a 0.80m (32") long test section in the center. Room air entered the wind tunnel through a furnace filter (0.41m x 0.50m x 2.5e-2m (16" x 20" x 1"); American Air Filter, Louisville, KY) then passed through three perforated metal screens (60 percent, 40 percent, then 33 percent open area) that acted as a settling means so airflow approaching the test section was uniform. The inlet filter was placed 0.10 m (4") from the end of the wind tunnel and the outlet filter was 0.43 m (17") from the other end. The first metal screen was 0.10m (4") from the inlet filter and the screens were spaced 0.10 m (4") apart. Detailed drawings of the wind tunnel are presented in the figures 4.01 to 4.03, while a picture of the wind tunnel with the cage in the parallel orientation is shown in figure 4.04.

The instrumented mouse cage was made from a standard Lab Products, Inc., shoebox mouse cage with approximate top dimensions of 0.18m x 0.28m x 0.13 m (7" wide x 11" long x 5" high) (see figures 4.05 to 4.11). The filter top was the high profile type and the filter was a Reemay #2024, 2.1 oz/yd^2, 12 mils thick. The cage had approximately 1.25e-2m (0.5") of hardwood shavings bedding on the floor, a wire rack, water bottle, and simulated feed.

The cage also contained one of two mouse heater representations: a simple, small electric heater, that will be known hereafter as the default mouse heater (DMH) (shown in figure 4.12); and a more realistic representation of the physical presence and heat transfer characteristics of the mice huddle, that will be know hereafter as the simulated mouse object (SMO) (shown in figure 4.13). In the cases that included the DMH, the cage had an electric heater placed on the bedding towards the front of the cage that produced heat equivalent to the total heat production of five mice weighing 2.0e-2 kg (4.4e-1 lb) each, 2.3 W. Heat production simulated was based on the ASHRAE (1993) equation:

$$ATHG = 2.5\ M \qquad (4.1)$$
$$M = 3.5\ W^{0.75}$$

Where:

ATHG = average total heat production from laboratory animal, W/animal
M = metabolic rate of animal, W/animal
W = mass of animals, kg

The DMH was a 200 ohm precision resistor with approximately 21.5 V of direct current from a regulated, filtered D.C. power supply.

In the cases that included the SMO, the cages included a more accurate mice huddle representation, that was placed within the cage at a location centered width-wise and towards the front one-third in the same location as the resistor heater (see figures 4.08 to 4.10). The SMO was designed to simulate five mice for volume obstruction, sensible heat production, and surface temperature. The mice were simulated using 2.20e-1m (7/8") outside diameter PVC pipe. The pipe had a wall thickness of 2.4e-3m (3/32") and was cut to 4.3e-2m (1-11/16") lengths. The ends of the pipe were covered with duct tape and plastic caps (see figures 4.13 and 4.14). Sensible heat was simulated using one 200 ohm precision resistor powered at 9 volts per pipe. Before starting the experiment the surface temperature of the SMO was measured several times at various locations, using a Cole Palmer infrared thermometer (see figure 4.14), and shown to closely correspond to those found on the fur of the dorsal surface of mice by Chris Gordon (about 26.7 °C (80.0 °F)). Justification for the physical sizing of the SMO is given in appendix I: section 2.3.

In both mouse heater representations, a voltage regulator (Epsco model EFB) was used to produce the voltage. The voltage was constantly monitored using a Fluke 75 multi-meter. Resistance was checked at the beginning of each experiment with the Fluke to guarantee the resistor was in working order.

The cage was instrumented to measure air velocities approaching or moving past the cage on all four sides, at approximately the top edge of the cage, or the lip of the top. An air velocity sensor was placed on each of the four sides at approximately 2.0e-2m (0.75") distance out from the cage at the midlength of each side. Air velocities, temperatures, and air exchange rates were measured

inside the cage. Air velocities and temperatures were measured with thermistor based BESS Lab air velocity sensors and type T thermocouples, respectively. Six air velocity sensors were placed approximately 2.5e-2m (1") above the bedding and uniformly spaced around the cage at this level. Six thermocouples were placed approximately 2.5e-2m (1") from each air velocity sensor at the same height. A Campbell 21X data logger with an AM416 Multiplexer collected cage sensor outputs.

Exact sensor locations, cage dimensions, and cage locations within the wind tunnel are available from the drawings in the figures 4.01 to 4.13.

4.1.1.3 Experimental Data Sets Considered

There were nine series of experimental scenarios considered in this project:

Series Set Base

In this series of experiments, the tracer gas used to determine the ventilation rate was exclusively 99.8 percent purity CO_2, that was injected (and sampled) at a rate of 1 L/min into the cage. The approaching air impacted the cage in three different orientations: the parallel orientation, in that the tunnel air moved horizontally towards the front edge of the cage; the perpendicular orientation, in that the tunnel air moved horizontally towards the side of the cage; and the vertical orientation, in that the tunnel air moved vertically downwards towards the top of the cage. These three orientations are summarized in figures 4.01 to 4.03. In each orientation, the air velocities approaching the cage were 15, 20, 30, 40, 50, 60, 70, 80, 90 and 100 fpm (0.075, 0.10, 0.15, 0.20, 0.25, 0.3, 0.35, 0.40, 0.45 and 0.5 m/s respectively).

Series Sets One and Two

It was decided that the injection rate of CO_2 utilized in series set base was too large in comparison with the likely gaseous generation rates from the mice in the actual physical case, and that the magnitude of the injection could affect the flow field conditions within the cage, i.e., the gas would no longer act as a tracer gas. Also, it was decided that the higher end of the velocity range chosen, i.e., 0.3 m/s (60 fpm) and above, was unlikely to be present in the animal room facility close to the cages.

In series sets one and two therefore, the injection rate was reduced to more realistic levels, and the tunnel approach velocity range was clipped at 0.25 m/s (50 fpm). In both series set one and two, the injection (and sampling) rate was set at 100 mL/min: in series set one, the tracer gas used was 99.8 percent purity CO_2; in series set two, the tracer gas used was 4.99 ppm SF_6. The tests ran at 15, 20, 30, 40 and 50 fpm (0.075, 0.10, 0.15, 0.20 and 0.25 m/s respectively). The parallel and perpendicular orientations were both considered.

Series Set Three

In the third series set, the parallel cage orientation with CO_2 tracer gas was repeated with the heater on and the heater off for only the 20 and 40 fpm (0.10 and 0.20 m/s) air velocities to determine if the heater had a significant effect.

Series Sets Four and Five

Series sets four and five compared two tracer gas methods: the decay method and the constant injection method. In both methods, CO_2 was injected at 100 mL/min (3.53e-3 ft^3/min) in the same locations as in series set one. A simulated mice obstruction (SMO) occupied approximately the same volume, produced the same sensible heat, and had approximately the same surface temperature as five mice in a tight group. The tests were run at three approach air velocities: 20, 30 and 40 fpm (0.10, 0.15 and 0.20 m/s respectively), and three cage orientations to airflow (parallel, perpendicular and vertical).

It should be noted that the primary reason for the series set four experimental tests was to replicate and expand the work performed by Keller, White, Snyder, and Lang (1989). In particular, in that paper, the authors measured decay data for a cage that was orientated in the parallel direction, and was subject to an approach velocity of 16 fpm (0.08m/s). The cage used in the Keller, White, Snyder, and Lang (1989) paper was very similar to that used in this present study. The emphasis of this experimental data set is to demonstrate that the experimental procedure being utilized in the current study was technically correct, and that the cage considered was representative of a typical mouse cage.

Series Sets Six and Seven

Series sets six and seven were conducted with the filter lid on but with a seal around the lip edges so all airflow through the cage passed through the filter, or with the filter lid sealed and the lip edge open. These results were compared to the results from series set three. The tests were similar to series set three except for the sealed edge and top, only the constant injection method was used, and only the 20 and 40 fpm (0.10 and 0.20 m/s) air velocities were used with only parallel and perpendicular airflow orientations. Also, during part of this series set, the SMO was introduced into the cage in place of the resistor, as a heat source. Data were collected using a randomized complete block design with the lid condition being blocked. The SMO was always allowed to produce heat. The heater state and air velocity levels were randomized within each lid condition block.

Series Set Eight

Series set eight was conducted with pairs of cages together, as shown in figures 4.15 and 4.16. In these tests, two cages were considered side by side for both the parallel and perpendicular cage orientations with the spacing between the cages set to that that the cages would experience in an animal facility room. In particular, the spacing between the cages in both cases was set to 2.81e-

2m (1.11"). Only one tunnel velocity, 30 fpm (0.15 m/s) was considered for each orientation. Instrumentation was included in one cage only. The other cage was left basically empty.

These sets are summarized in table 4.1.01 below:

Table 4.1.01 Table of Cage Condition Experimental Series

Series Set	Tracer Gas	Injection Rate (L/ min)	Sampling Method	Mouse Heater Type	Cage Orientation	Tunnel Air Velocity Range (fpm)
Base	CO_2	1.0	Steady	DMH (On/ Off)	Par, Perp, Vert	15 – 100
One	CO_2	0.1	Steady	DMH (On only)	Par, Perp	15 – 50
Two	SF_6	0.1	Steady	DMH (On only)	Par, Perp	15 – 50
Three	CO_2	0.1	Steady	DMH (On/ Off)	Par, Perp, Vert	20, 40
Four	CO_2	0.1	Steady	SMO (On only)	Par, Perp, Vert	20, 30, 40
Five	CO_2	0.1	Decay	SMO (On only)	Par, Perp, Vert	20, 30, 40
Six	CO_2	0.1	Steady	DMH (On/ Off); SMO (On Only)	Par, Perp	20,40
Seven	CO_2	0.1	Steady	DMH (On/ Off); SMO (On Only)	Par, Perp	20, 40
Eight	CO_2	0.1	Steady	SMO (On Only)	Par, Perp	30

4.1.1.4 Experimental Procedure

4.1.1.4.1 Common Calibration Procedures

The following calibration procedures were performed before all experimental test series.

Thermocouple Calibration

During all of the results sets, the cage housed the same six T-type thermocouples. The thermocouples were calibrated at five temperatures using a water bath. Water bath temperatures were determined using a SAMA thermometer. Regressions were formed by comparing thermocouple readings to the thermometer readings. The thermocouples were connected to a Campbell 21x data logger when readings were taken. The regression equations were used to obtain predicted temperature readings. The standard error of the predicted readings vs. the thermometer readings was computed for each thermocouple. No standard error reading exceeded 9.0e-2 °C (1.6e-1 °F). Calibration results are presented in appendix I: section 2.1.1.

Cage Anemometer Calibration

BESS Lab thermal anemometer probes surrounded the cage for each result set. The sensors were calibrated using a TSI model 8390 Bench Top Wind Tunnel with a TSI model 8910 pressure transducer. Because of the relationship between anemometer performance and temperature, the calibration air was recycled in a closed loop to prevent temperature fluctuations. This was done by having the intake air of the calibrator come from an 2.44 m (8') x 1.22m (4') x 1.22 m (4') x 5.08e-2m (2") thick insulated box and directing the exhaust air back into the box (see figure 4.17). The insulated box was cooled for at least ten minutes using air from a chiller to about 20.0 °C (68.0 °F) at that time the box was sealed and the calibration started. The temperature was allowed to rise by conduction until a temperature near room temperature was reached. At this time a low power electric heater was turned on to obtain temperatures greater than room temperature. Each probe was subjected to velocities of 15, 20, 30, 40 and 50 fpm (0.076, 0.10, 0.15, 0.20, 0.25 m/s) and temperatures ranged from 20.0 °C to 29.3 °C (68.0 to 84.7 °F). Velocities within the calibrator were precisely calculated by the manufacturer and presented in a table that relates pressure differences to chamber velocities. Temperature and velocity sensor output voltage were taken every second and averaged over one minute using a Campbell 21x Data Logger.

Temperature and voltage data were analyzed to form trend lines for each velocity. The trend lines were used to generate predicted voltage values. The velocity data, temperature data, and predicted voltage values were then combined and plotted to form a contour map that had axes of velocity, temperature, and contours of voltage. The map was made using a third order polynomial regression. A third order polynomial regression was chosen because it provided an equation that could easily be used to determine velocity values within a spreadsheet and because it displayed contour lines that closely followed those lines displayed by other curve-fit methods. The contour map was made as a visual means of finding if values were not outside the calibration range, i.e. greater than 0.25 m/s (50 fpm) or less than 0.10 m/s (20 fpm). Calibration results are presented in appendix I: section 2.1.2.

Procedure to Set an Approach Velocity

The wind tunnel air velocity was determined by a calibrated thermal anemometer (IAT model AVS-94A-10X). The anemometer was placed in front of the cage, centered on the cage. Air velocity within the cage wind tunnel was adjusted using a voltage regulator (Variac Auto Transformer) to adjust fan speed, a bypass door, and for lower velocities, a pressure restriction. Velocities were adjusted until the desired approach air velocities (15, 20, 30, 40, 50, 60, 70 or 80 fpm (0.076, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35 or 0.40 m/s respectively)) were read from the anemometer, in the form of a corresponding voltage. Air velocities were controlled by a centrifugal fan (0.15m (approx. 6") diameter inlet) and exhaust was vented through a flexible conduit (0.20m (approx. 8" diameter)) to the outside.

Anemometer Calibration

The IAT AVS-94A was calibrated prior to each test in a wind tunnel calibrator (TSI model 8390). Velocities within the calibrator were precisely calculated by the manufacturer and presented in a table that related pressure differences to chamber velocities. To sense pressure differences within the chamber, a Dwyer Micro Detector micromanometer was used. As a safety check the micromanometer values were compared to pressure readings displayed by a digital pressure transducer (TSI model 8910). Calibrating the anemometer used to determine the approach air velocities required taking data at the desired approach air velocity (15, 20, 30, 40, 50, 60, 70 or 80 fpm (0.076, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35 or 0.40 m/s respectively). For each calibration temperature, sensor voltage, transducer reading, and micromanometer data were taken for the desired approach air velocity. Temperatures were taken near the calibrator using a SAMA mercury thermometer. The date and time of calibration was recorded. Calibrator pressures were regulated by adjusting the wind tunnel fan speed with a voltage regulator (Dart 250). Pressures were adjusted until they matched the pressures corresponding to the desired approach velocity. When the desired pressure was reached the sensor voltage was noted and the sensor was placed into the wind tunnel.

4.1.1.4.2 Specific Series Procedures

Siting of Sampling Tubes

The question of locating the sampling tubes was considered prior to the series set base experimental measurements. The cage air exchange rates were measured with the tracer gas method using CO_2 as the tracer gas. When tunnel air approaches a cage, air is drawn from one part of the cage and fresh air enters the cage at another location. Therefore, air has to be sampled at both the entering and exiting locations of the cage. Smoke sticks (titanium tetrachloride) were placed into the cage to visually determine the locations where air entered and exited the cage in order to determine the locations for the sampling locations. Refer to figures 4.05 through 4.10 for the placement of the air sampling tubes.

Series Set Base

Carbon dioxide (at least 99.8 percent pure, bone dry) was injected into the cage near the bedding at a rate of 1 L/min through two diffuser stones spaced 0.08m (3.15") apart. The injection rates were calibrated using a digital flow meter (Humonics 650 Digital Flowmeter). The injection rate was monitored continuously with a Gilmont (model 1260) calibrated flowmeter with an accuracy of +/- 2 percent. The CO_2 was injected at locations that allowed enough distance to mix well with the cage air before it was sampled at the cage exhaust area. The injection locations were also determined with smoke tests and are presented in figures 4.05 to 4.07.

Air was sampled from two sampling tubes at different locations in the cage to determine CO_2 content of air exhausting from and air entering into the cage as discussed above. The cage airflow was allowed to stabilize for ten minutes before samples were drawn. Sampling rate was 1 L/min at each location but samples were not drawn from both locations at the same time: a two minute minimum stabilization time was allowed between sampling the front and back locations of the cage. Consequently, at all sampling times, 1 L/min of CO_2 was injected into the cage and 1 L/min of air/ CO_2 mixture was removed from the cage by the sampling system. Sampling air was drawn from the cage with a SKC Airchek Sampler pump and the flow rate was checked against the Gilmont (model 1260) flowmeter prior to and during the experiment. Sampling was taken through tubes with five uniformly distributed holes to obtain an average CO_2 concentration over a distance since the concentration varies with location, figure 4.18. CO_2 concentration also varied slightly over time so the samples were drawn for five minutes into a gas sampling bag (Tedlar, polyvinyl fluoride), then the concentration in the bag was measured to determine the average concentration over the five sampling locations and over the five minute period. Three bags of gas samples were taken at the air exiting location and one at the entering air conditions. The same sampling procedure was used as for the exhaust air. CO_2 levels in the gas sampling bags were measured with a Beckman LB2 carbon dioxide infrared gas analyzer (Beckman Instruments, Inc.). The analyzer calibration was compared to two certified gases (0.55 percent and 1.58 percent CO_2) prior to each use. Before the bags were used again they were emptied using a vacuum pump to remove any accumulated CO_2. The tubing system going into the analyzer was checked for leaks before any concentration readings were taken. The analyzer was calibrated by first adjusting the instrument zero dial to match the lower concentration and then by adjusting the gain to match the higher concentration.

To monitor the possibility of CO_2 buildup in the test room, a CO_2 analyzer (Fuji Electric model ZFP5YA31) was periodically turned on and background CO_2 concentrations were taken.

Series Sets One and Two

The same injection/sampling procedures as followed in series set base were maintained for series set one, but for series set two, that considered SF_6 as the tracer gas, the procedures were somewhat different.

The SF_6 was injected through Teflon tubing. Teflon was used to prevent SF_6 absorption/ readmission problems that are characteristic of that class of gas.

Three SF_6 samples were removed from both the front and back locations of the cage using syringes (GASTIGHT #1750). The syringes pierced a rubber septum in the tubing that ran to the billows pump and was connected to the tubing by a T–joint. After piercing the septum, each syringe was repeatedly filled and emptied into the tube three times before an approximately 0.5mL (3.05e-2in^3) sample was withdrawn.

The SF_6 concentrations were measured with a Varian 3700 Gas Chromatograph (GC) with an Electron Capture Detector. The 0.25mL (1.53e-2in^3) samples of standard gas mentioned above were injected from precision syringes into the Varian through a frequently changed septum. The Varian was attached to a printer that produced a concentration peak graph and gave the SF_6 concentration. Syringe labels were recorded on the graph and the process repeated. After every syringe concentration had been recorded, each syringe was dismantled and cleaned by blowing compressed air through it and onto its pull.

The GC was calibrated using a one-point calibration with a 500 ppb standard gas. 0.25ml (1.53e-2in^3) samples of standard gas were injected into the GC repeatedly until consistent, sharp peaks were obtained on the output chart. The calibration was checked with the standard gas after every three sets of injections. The GC was recalibrated when the expected sharp, consistent peaks were not seen on the output chart.

To monitor the possibility of SF_6 buildup in the test room, wind tunnel entrance samples were taken to measure the background SF_6 concentration. To further safeguard against SF_6 buildup, all air exiting the billows pump was bagged. Along with these measures all exhaust air from the wind tunnel was ducted outside of the room.

In both series, data were collected using a randomized complete block design with the tracer gas and air velocity level being randomized.

Series Set Three

The same injection/sampling procedure was followed as for series set base. Data were collected using a randomized complete block design with the heater state and air velocity level being randomized.

Series Sets Four and Five

A standard concentration of CO_2 [99.8 percent] was used as the tracer gas. Injection rate was set at 100 mL/min (3.53e-3 ft^3/min). The injection rates were calibrated using a digital flow meter (Humonics 650 Digital Flowmeter). Digital flowmeter measurement, time, and date were recorded for each calibration. The injection rate was measured continuously with a correlated flowmeter (Gilmont, tube size 1, accuracy +/-2 percent of reading). Tracer gas was injected

through two diffuser stones that were spaced 0.08m (3.15") apart. CO_2 injector location varied with cage orientation (see figure 4.05 to 4.10 and 4.19). Two tracer gas methods were conducted simultaneously: the decay method and the constant injection method.

All sample concentrations were measured using a Beckman CO_2 Analyzer. CO_2 samples were pulled into the Beckman Analyzer using the analyzer pump. Flow through the analyzer was monitored and controlled using a flow controller/monitor. The flow was held constant at 469 mL/min (1.66e-2 ft^3/min). Flow rate readings were checked using a digital flow meter (Humonics 650 Digital Flowmeter) once daily. To produce an effective average flow rate of 100 mL/min (3.53e-3 ft^3/min), at 469 mL/min (1.66e-2 ft^3/min) of air was pumped out of the cage for 20 seconds with a 73.8 second waiting period during that background CO_2 concentration was measured. All wind tunnel exhaust air was ducted outside of the room.

The analyzer was calibrated using 1.58 percent and 0.55 percent standard concentrations of CO_2. The analyzer was calibrated by first adjusting the zero dial to match the lower concentration and then by adjusting the gain to match the higher concentration. This was done at the beginning of each experiment.

Samples from a bag of standard gas were drawn at the beginning of each day from each of three points that corresponded to those used during the decay method (see figure 4.20) and analyzed as a means of detecting leaks within the system. A leak was present if the concentration pulled through the sampling lines did not correspond to the known concentration within the bag. These values were recorded on the strip chart.

Cage CO_2 concentration was monitored at each cage decay location. Solenoid valves and Viewdac computer software were used to control from that cage location each sample was drawn. Concentrations were monitored from the beginning of injection until stabilization had been reached. Stabilization was defined as the point when two consecutive readings at all three decay sampling points were constant. Once stabilization had been reached, data collection from the decay sampling points were stopped. At this time constant injection sampling began. Constant injection data were recorded for 20 seconds at both the front and back locations of the cage with a 73.8 second pause between readings. The constant injection method samples were taken at various locations depending on cage orientation (see figures 4.05 to 4.07).

Once constant injection data had been taken, the decay method began. Soon after starting the decay method, the tracer gas flow was stopped. All decay samples were taken sequentially from one of three zones. Sequential data collection sequences for the decay method were randomly chosen from one of the six possible sequences that could be formed with three numbers.

Series Set Six and Seven

In results sets six and seven, tests was conducted with the filter lid on but it was sealed with putty around the lip edges so all airflow through the cage had to pass through the filter in the top, or it

was sealed on the filter top with plastic so all the airflow had to pass through the lip edge. The basic injection/sampling procedure as used in series set base was used in these series.

Each airflow orientation and lid condition was randomized separately. Data collection was randomized using randomized complete block design with the airflow orientation and the lid condition being blocked. The tracer gas method and air velocity levels were randomized within each block. The heater state and air velocity levels were randomized within each lid condition block.

Series Set Eight

As noted above, only one of the cages was instrumented in these tests. The basic injection/ sampling procedure as used in series set base was used in these series.

4.1.1.5 Methodology for Calculation of Cage ACH

The cage ventilation rate for all steady state injection cases was calculated from (Bennett and Myers (1982)):

$$Q = (C_S Q_S - C_O Q_S)/(C_O - C_I) \quad (4.2)$$

Where:

- Q = cage ventilation rate, ft^3/min
- C_S = CO_2 or SF_6 concentration of tracer gas:
  99.8 percent for CO_2;
  4.998ppm for SF_6
- Q_S = rate of tracer gas injection and air sampling from cage:
  3.53e-2 ft^3/ min for 1 L/min cases;
  3.53e-3 ft^3/min for 100 mL /min cases;
- C_O = CO_2 or SF_6 concentration of air exiting cage, percent
- C_I = CO_2 or SF_6 concentration of air entering cage, percent

The cage ventilation rates were adjusted to standard air density conditions at sea level (Barometric pressure = 29.92" of Hg) and 70 F by multiplying by a factor K.

$$K = (29.92/\text{Barometric Pressure, in. Hg}) \times ((490 + \text{air temp. F})/(460+70)) \quad (4.3)$$

This procedure was followed for both the experimental and CFD results.

4.1.1.6 Graphical Representation of Experimental Data

The graphical representations of the experimental data sets are shown in figures 4.21 to 4.31. The obvious trend to be seen in all the steady state plots is that the cage ventilation rate increases with an increase in approach velocity. The principal conclusion here is that the environment external

to the cage will therefore have an impact on the ventilation within the cage; higher external flow velocities will result in better cage ventilation. The tabulated and the graphical representation of all the data is presented in appendix I: section 2.2, while the comparison between the CFD and experimental data, intended as a means of validating the CFD cage model, is given in section 4.2.1.2.2.

The decay data is interesting in that it can be compared against previous work. In the case of a decaying concentration within a volume, the level of concentration remaining can be calculated from:

$$C = Co\, e^{-\lambda t} \qquad (4.4)$$

Where:

C	-	percent concentration, at time t
Co	-	percent initial concentration, at t = 0
λ	-	Decay constant

As the level of initial concentration varies from case to case, it is more convenient to normalize the decay such that the initial concentration is considered as 100 percent. The time taken to decay by a certain amount can then be tabulated. Table 4.1.02 below compares the time taken to decay the concentration by 90, 95 and 99 percent for the cage considered in Keller, White, Snyder and Lang (1989), and the parallel orientation cases considered in series set five.

Table 4.1.02 Time taken to decay concentration by 90, 95 and 99 percent for Keller, White, Snyder and Lang (1989) cage, and series set five: parallel orientation results.

Tunnel Velocity (fpm)	Time to Decay (min)		
	90 percent	95 percent	99 percent
Keller, White, Snyder and Lang Paper @ 16 fpm (May 1989)	18.27	23.77	36.54
20	16.69	21.27	33.37
30	12.38	16.11	24.76
40	11.29	14.68	22.57

Further, figure 4.31 displays the comparison between the series set five: parallel orientation results and the results presented in Keller, White, Snyder and Lang (1989) with the concentration levels normalized such that the initial concentration is considered as 100 percent.

The plot and table 4.1.02 clearly shows that the current data are entirely consistent with those data presented in the previous study. There are two conclusions to be drawn from this comparison:

- The experimental procedure followed in this section of the study, as well as the method for determining the decay characteristics of the cage, were consistent with other experimental studies.

- The cage used in this section of the study is a typical microisolator type cage, not a cage fabricated to exhibit certain characteristics.

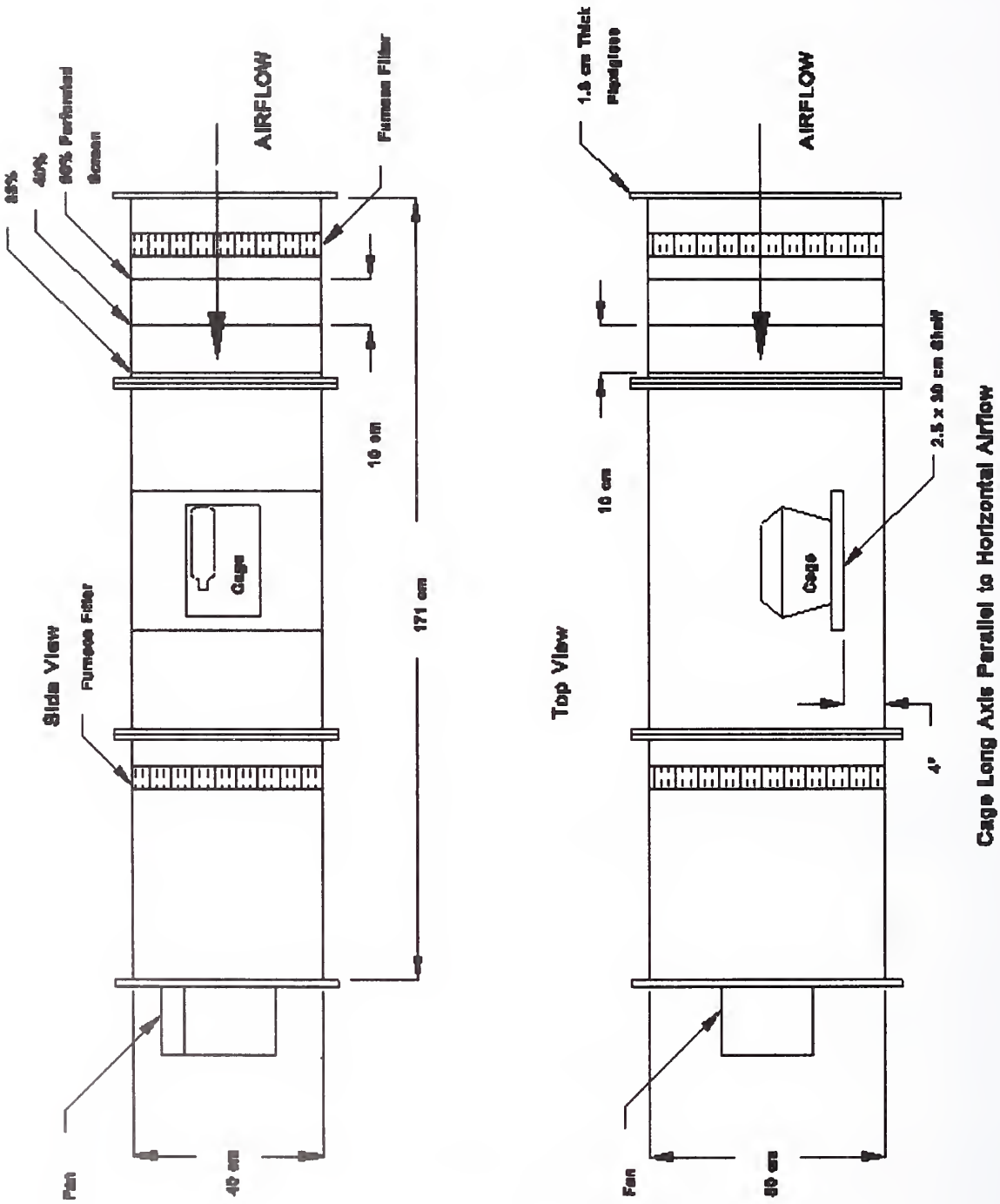


Figure 4.01 Parallel Cage Orientation Layout.

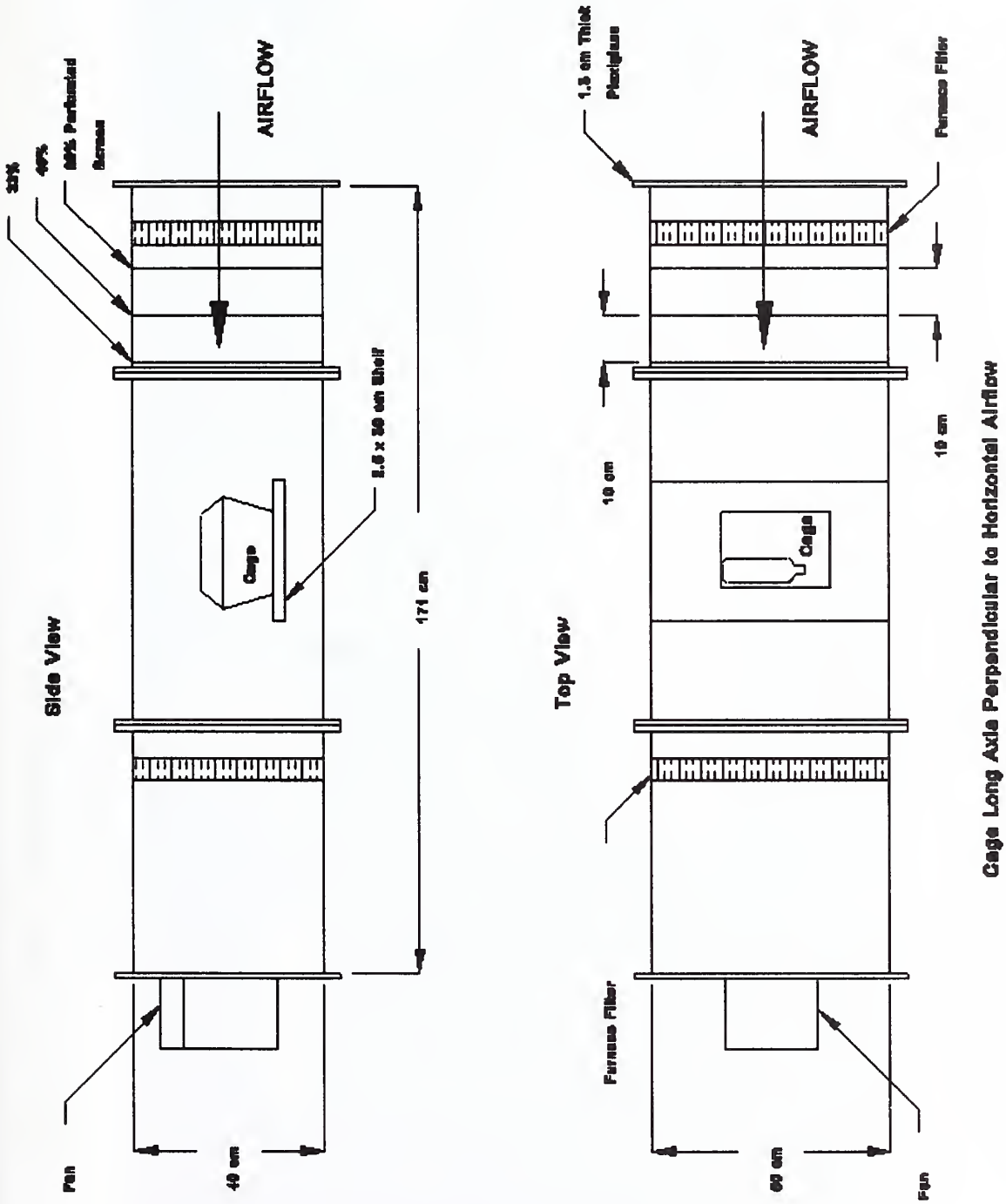


Figure 4.02 Perpendicular Cage Orientation Layout.

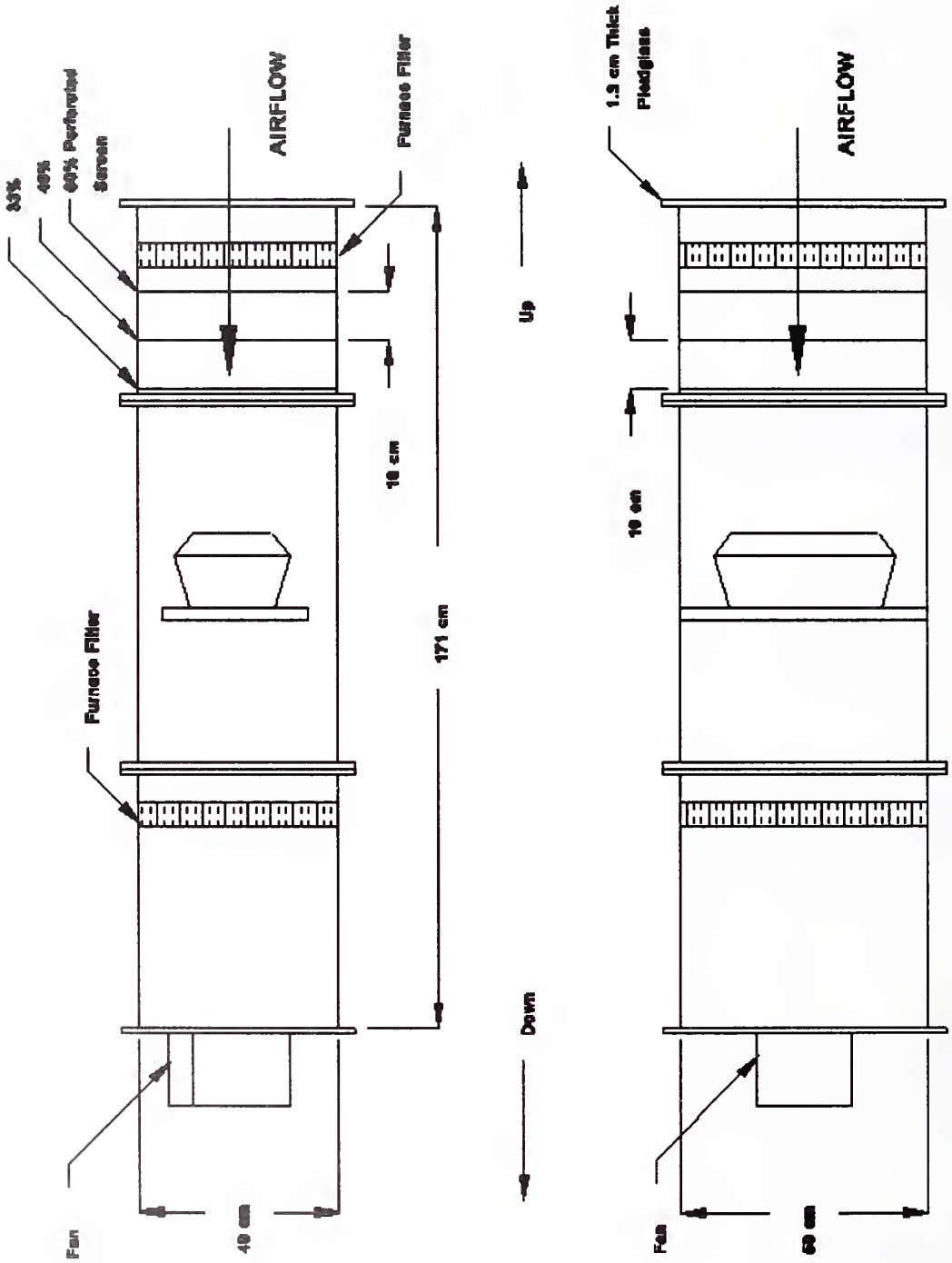


Figure 4.03 Vertical Cage Orientation Layout.

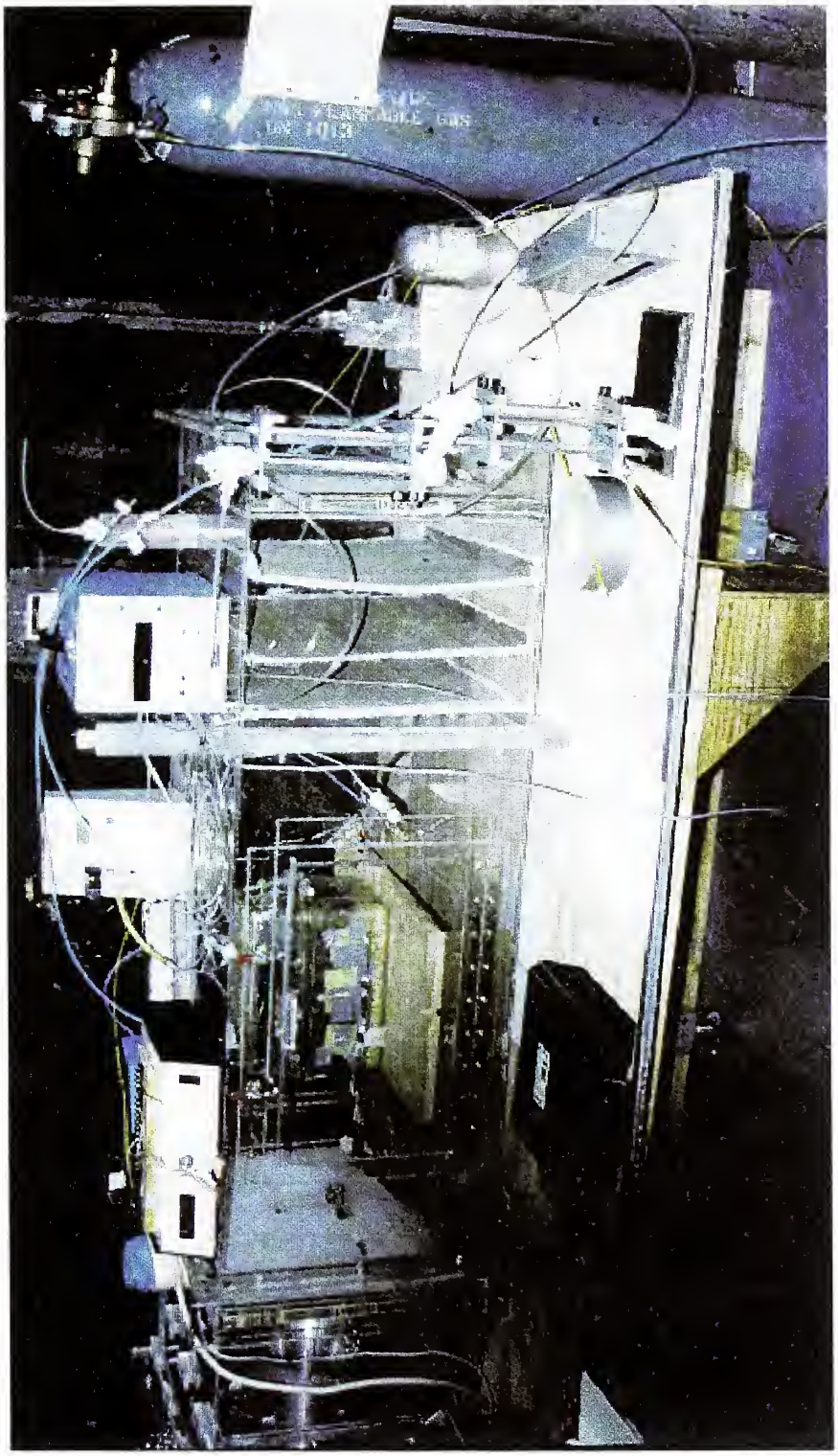


Figure 4.04 Wind Tunnel with Cage in Parallel Orientation.

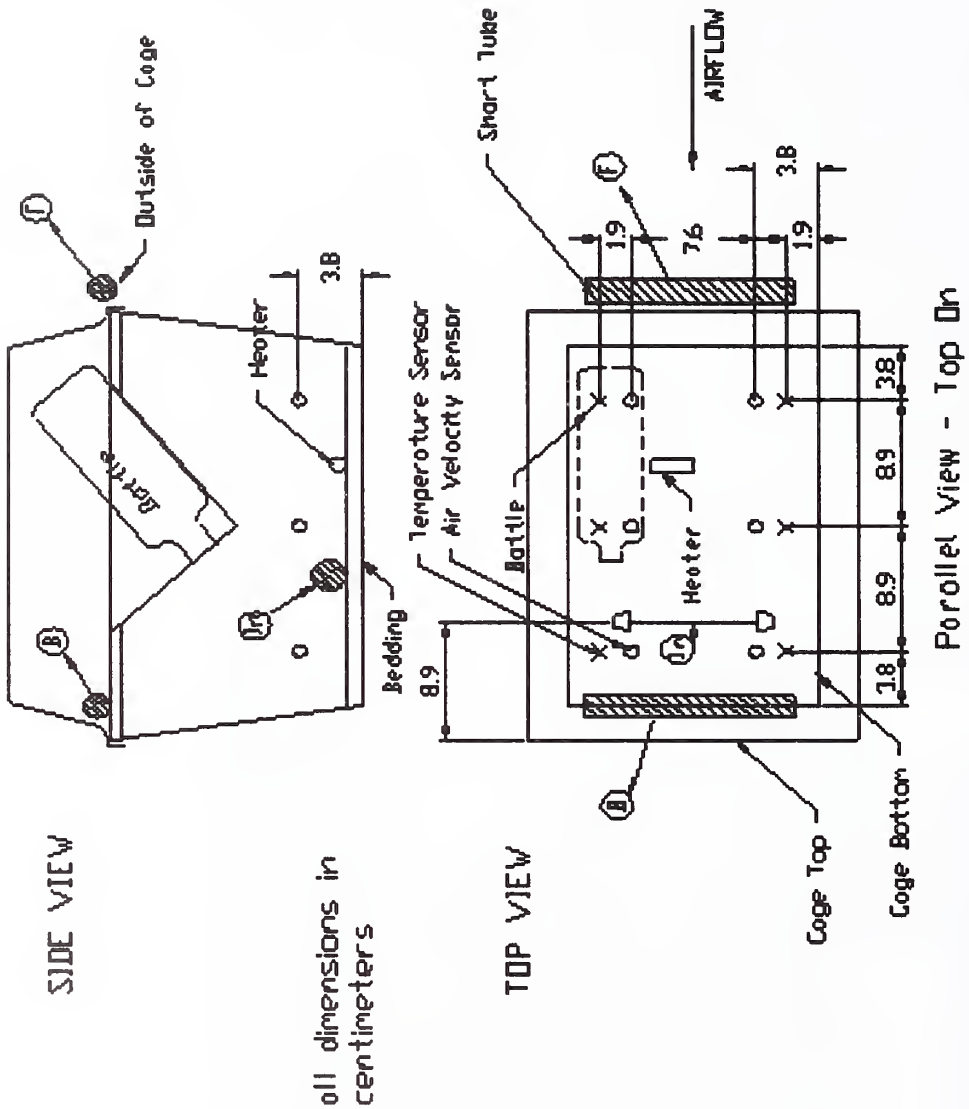


Figure 4.05 Sensor, air inlet and sampling location for cage parallel to horizontal airflow. Mouse Heater Representation: DMH.

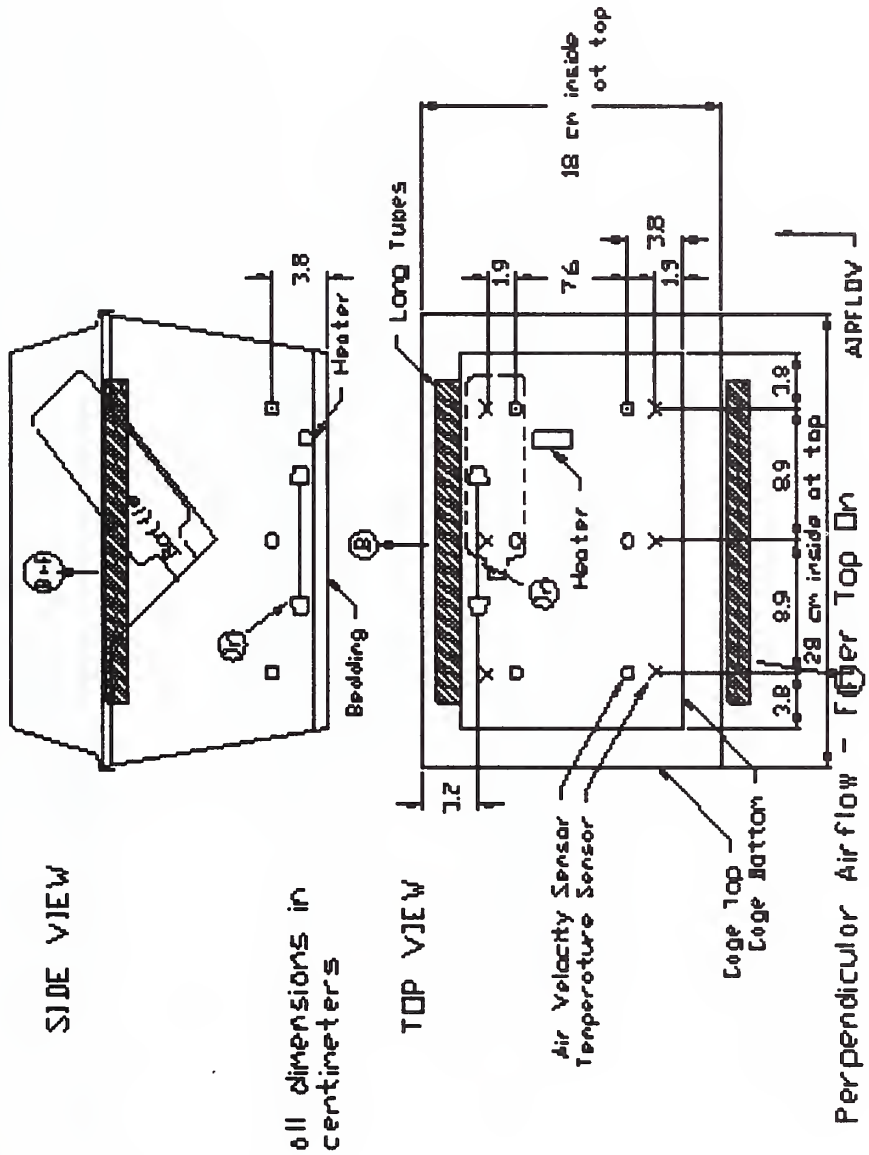


Figure 4.06 Sensor, air inlet and sampling location for cage perpendicular to horizontal airflow. Mouse Heater Representation: DMH.

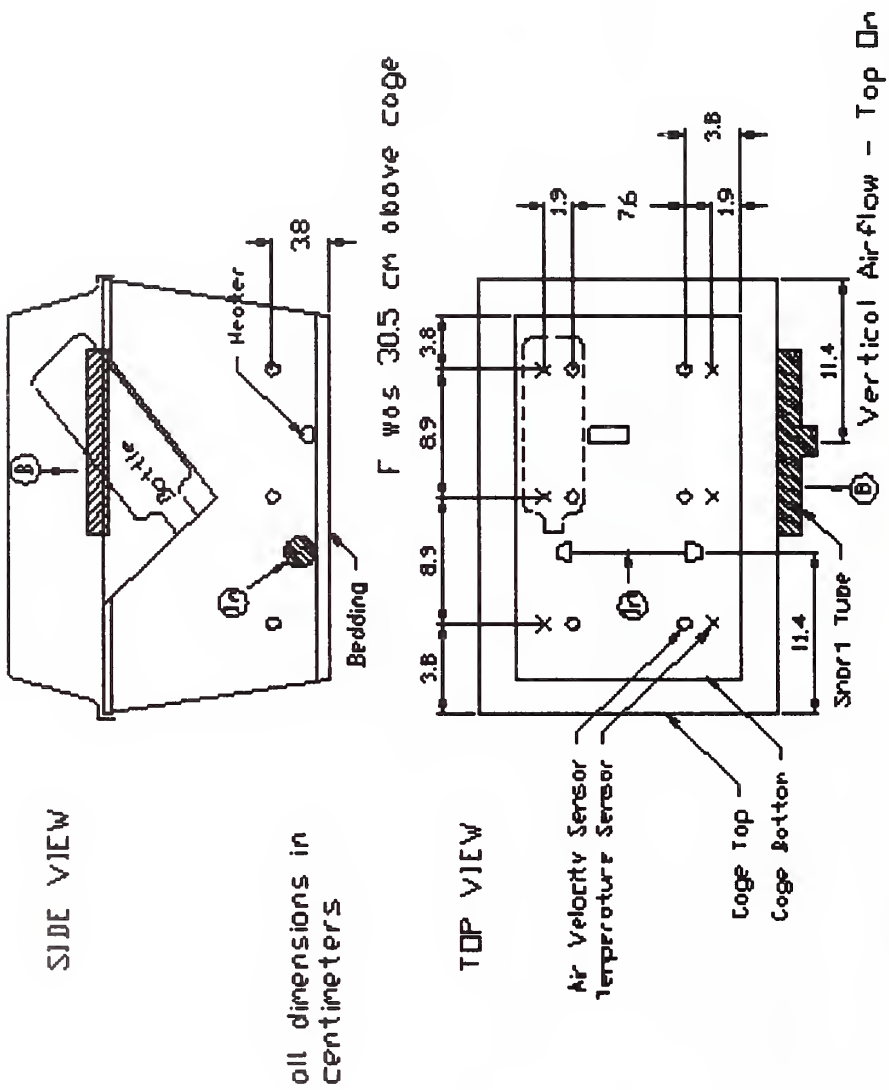


Figure 4.07 Sensor, air inlet and sampling location for cage vertical to horizontal airflow. Mouse Heater Representation: DMH.

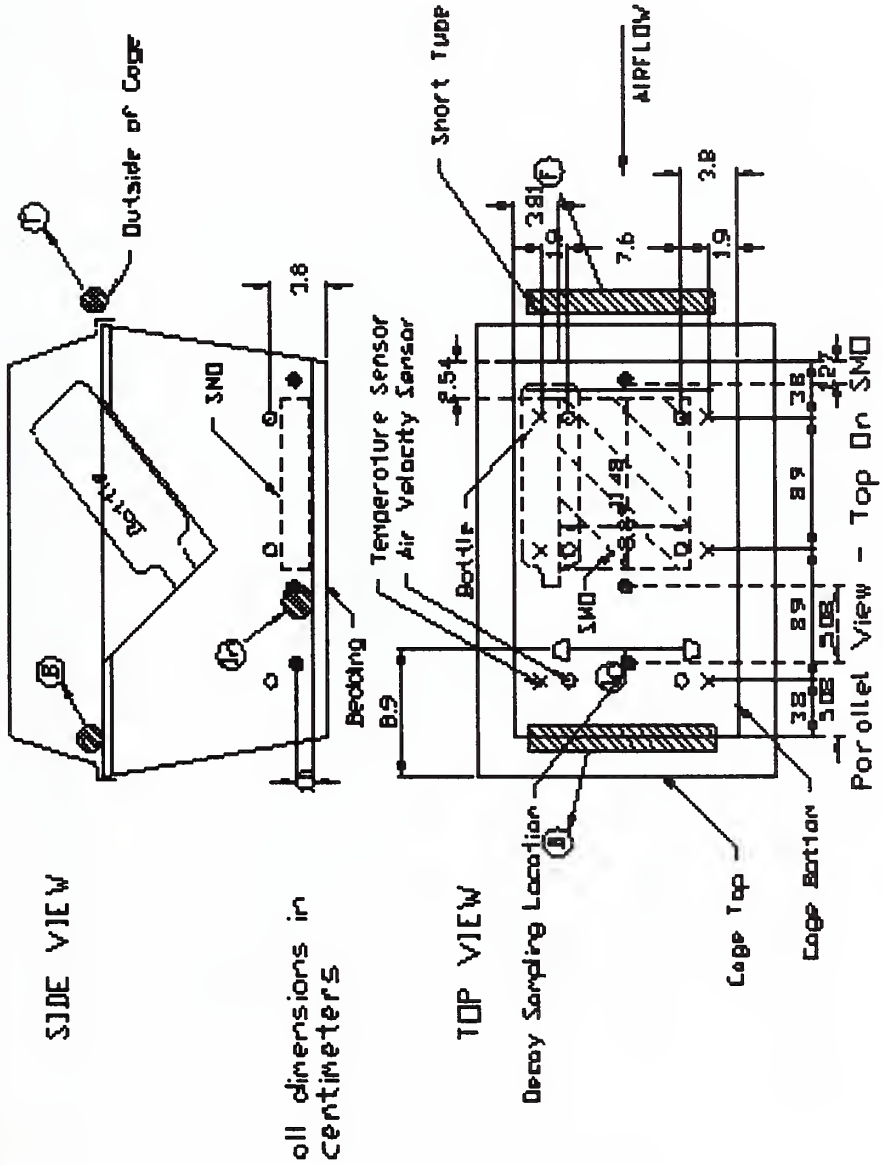


Figure 4.08 Sensor, air inlet and sampling location for cage parallel to horizontal airflow. Mouse Heater Representation: SMO.

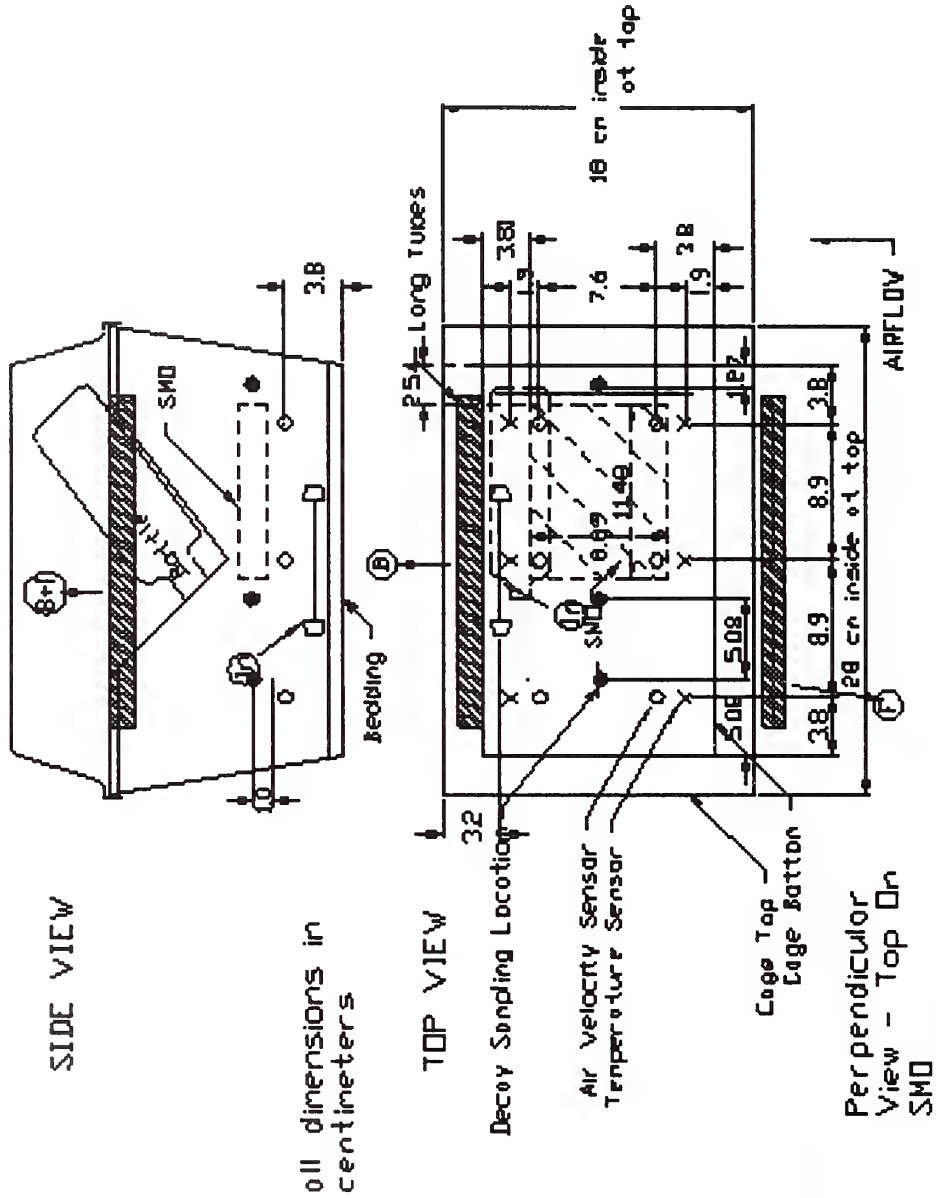


Figure 4.09 Sensor, air inlet and sampling location for cage perpendicular to horizontal airflow. Mouse Heater Representation: SMO.

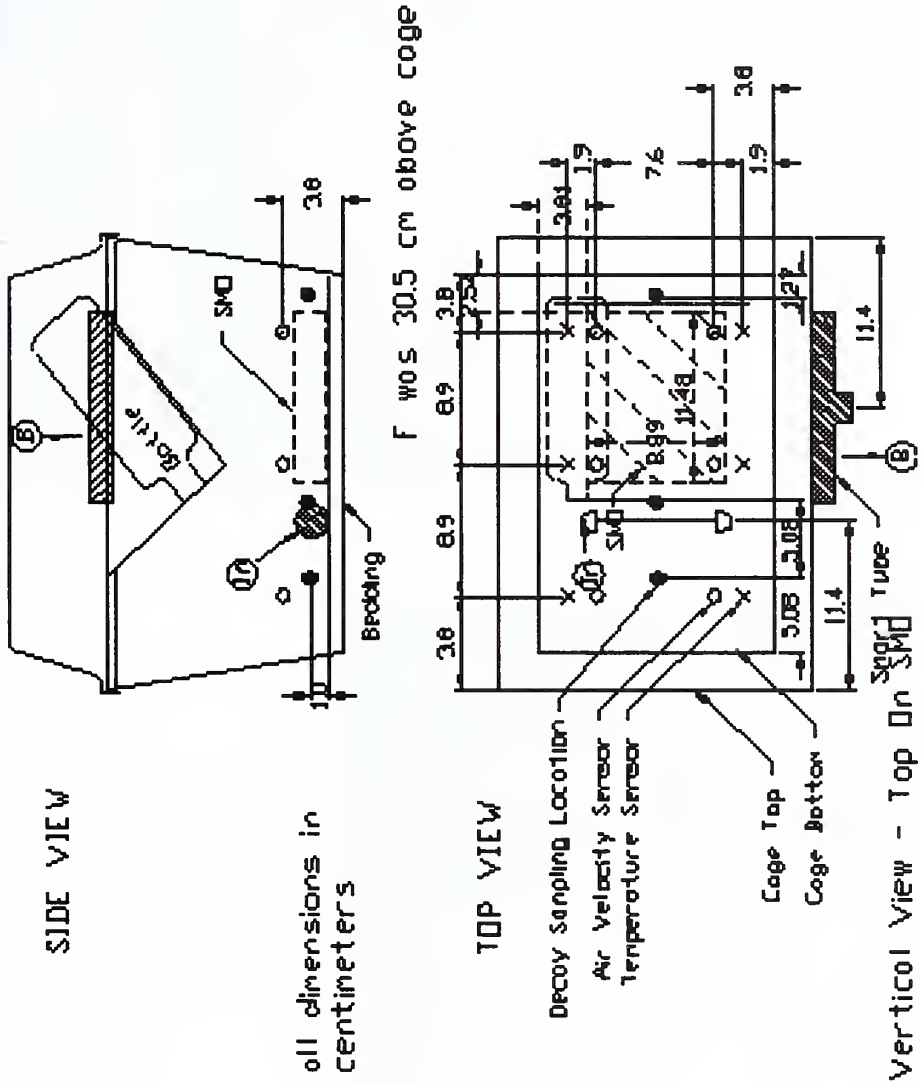


Figure 4.10 Sensor, air inlet and sampling location for cage vertical to horizontal airflow. Mouse Heater Representation: SMO.

Figure 4.11 *Microisolator with Sampling Tube.*

Figure 4.12 *Default Mouse Heater (DMH).*

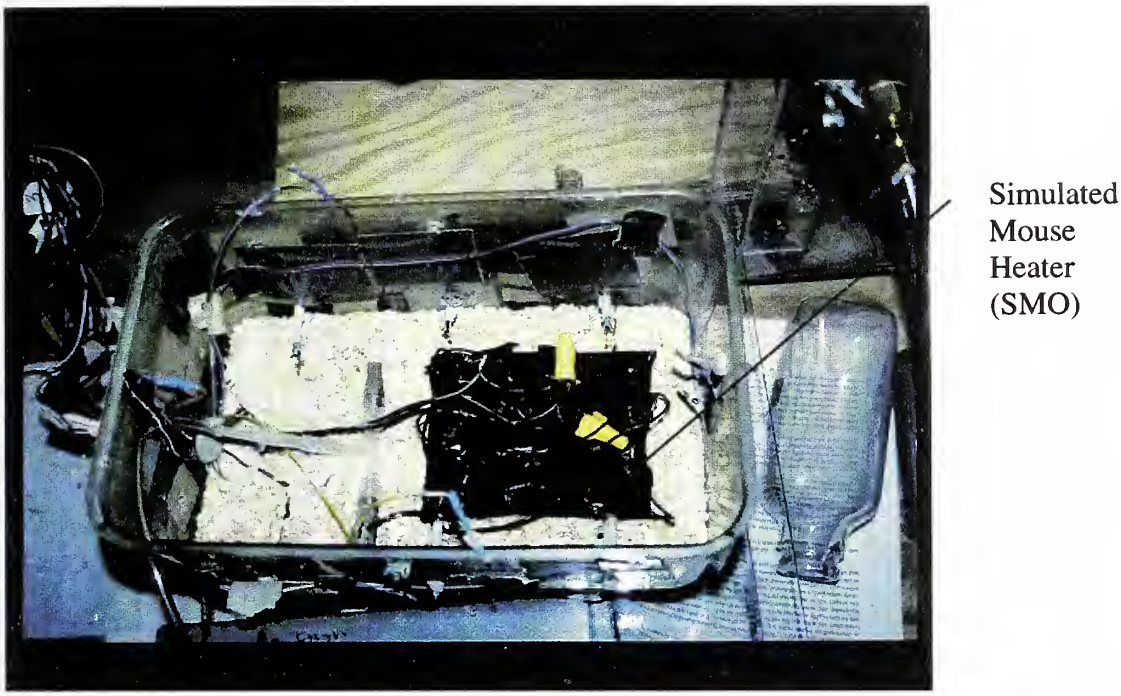


Figure 4.13 *Simulated Mouse Heater (SMO).*

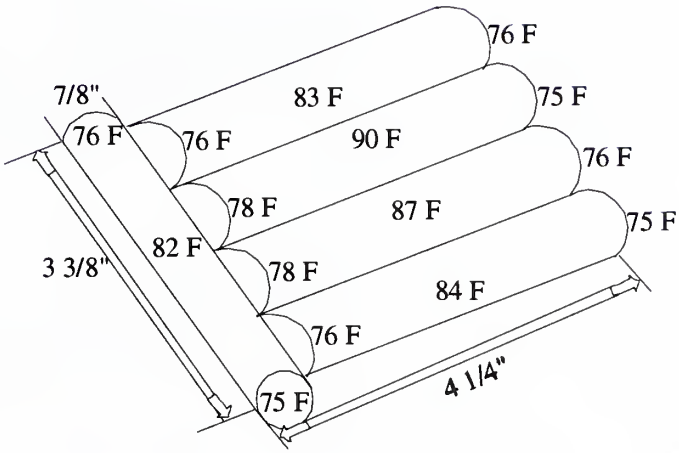


Figure 4.14 *Simulated Mouse Object (SMO) with surface temperatures and dimensions.*

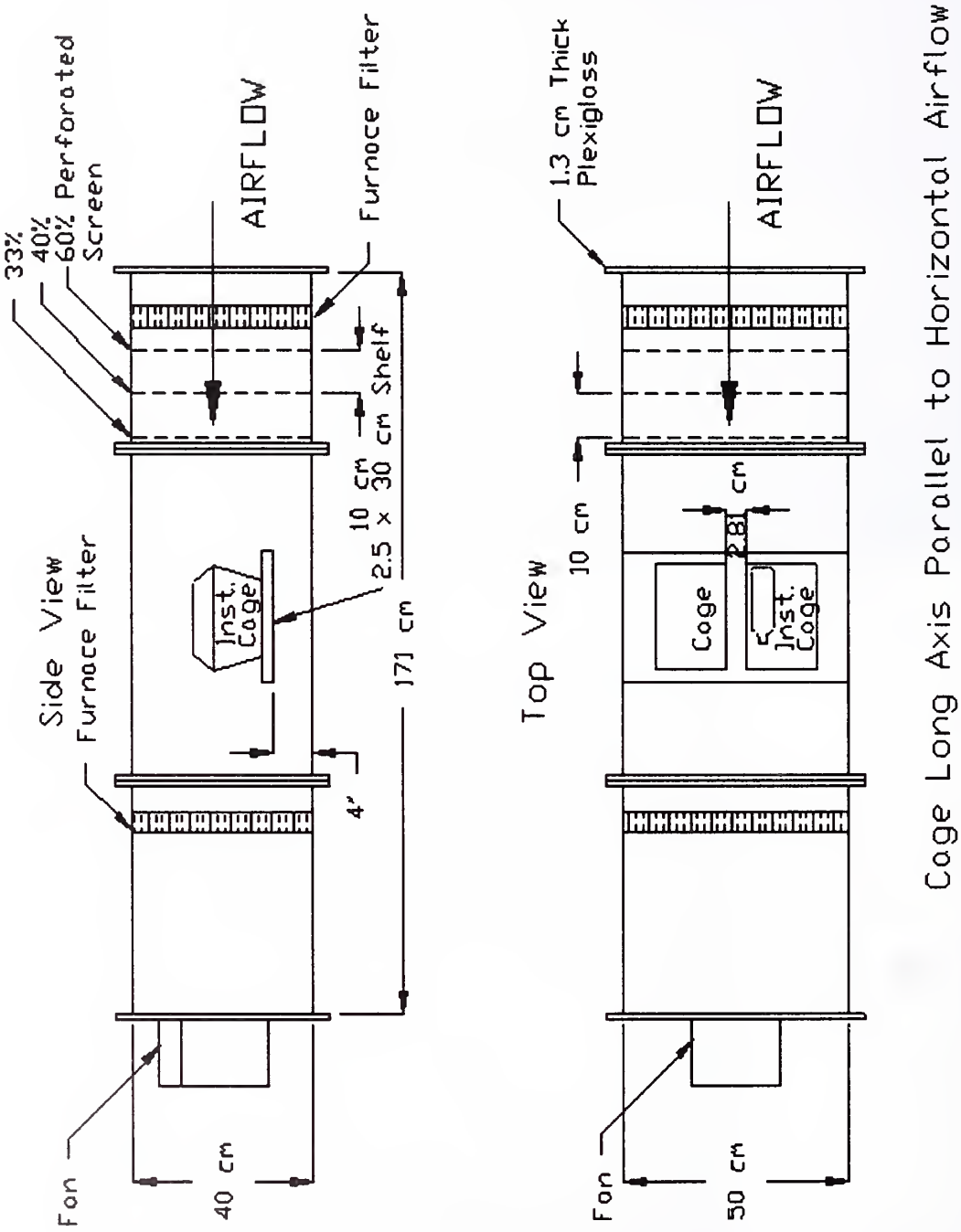


Figure 4.15 Experimental Set-Up for Series Set Eight: Parallel Cage Orientation.

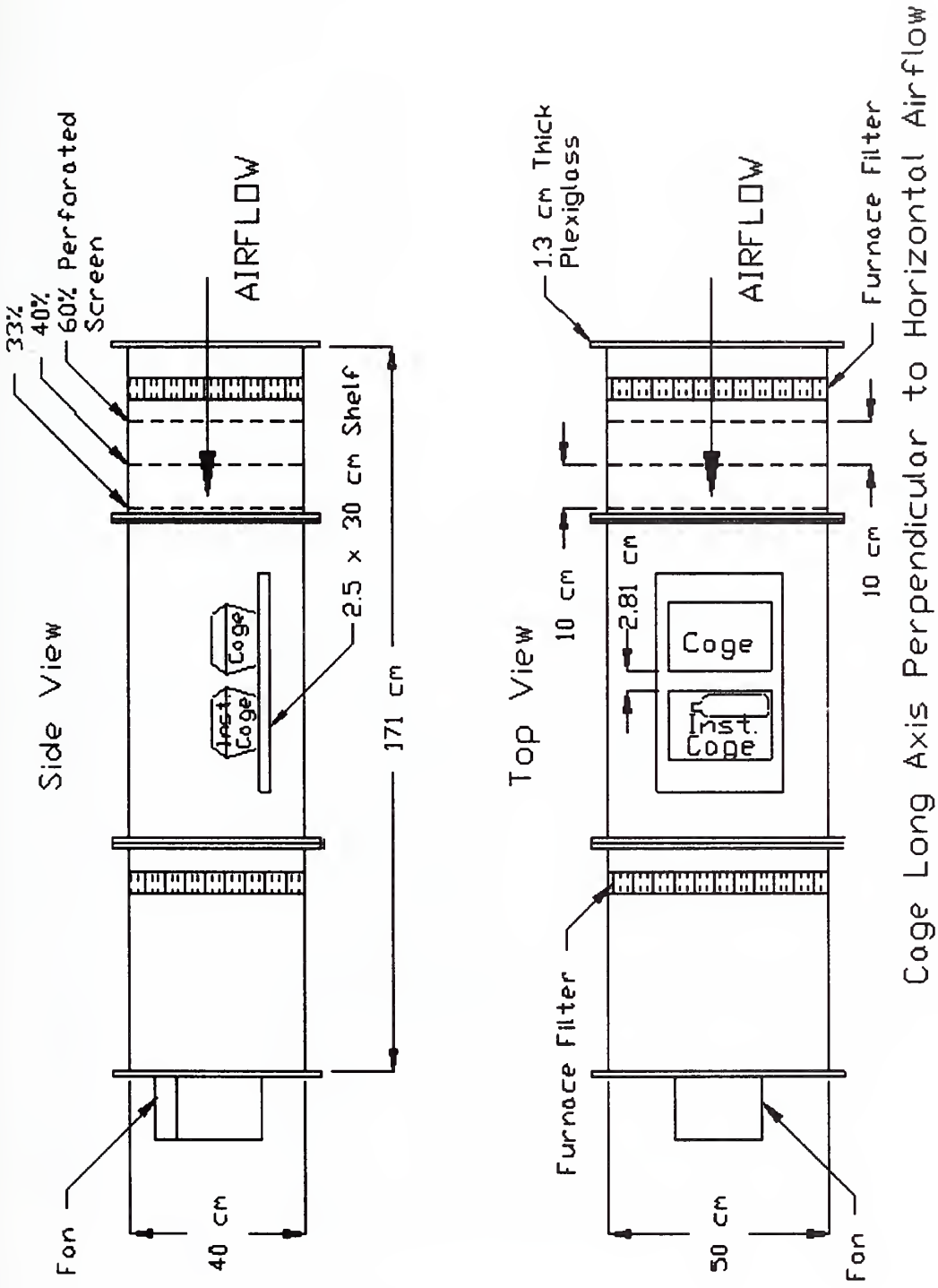


Figure 4.16 Experimental Set-Up for Series Set Eight: Perpendicular Cage Orientation.

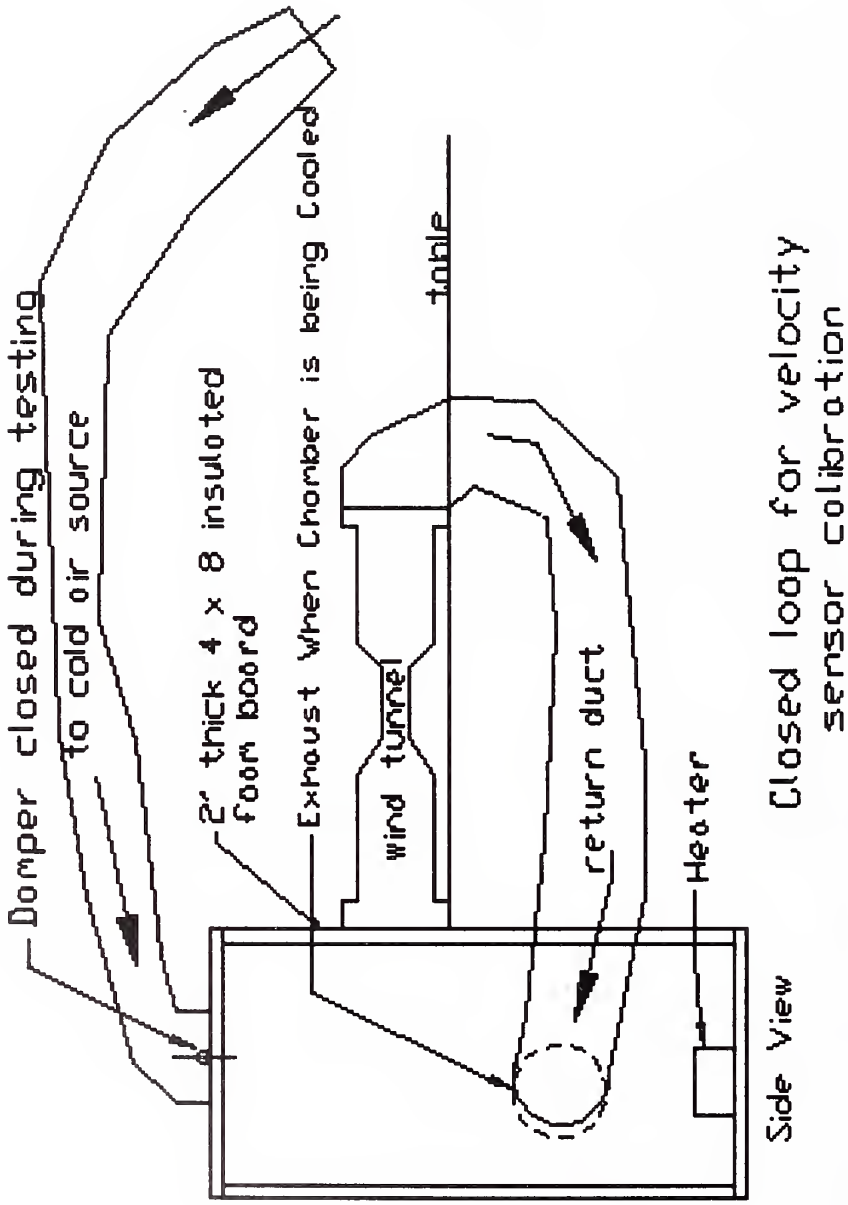


Figure 4.17 Diagram of the closed-loop system used with precise velocity sensor calibration.

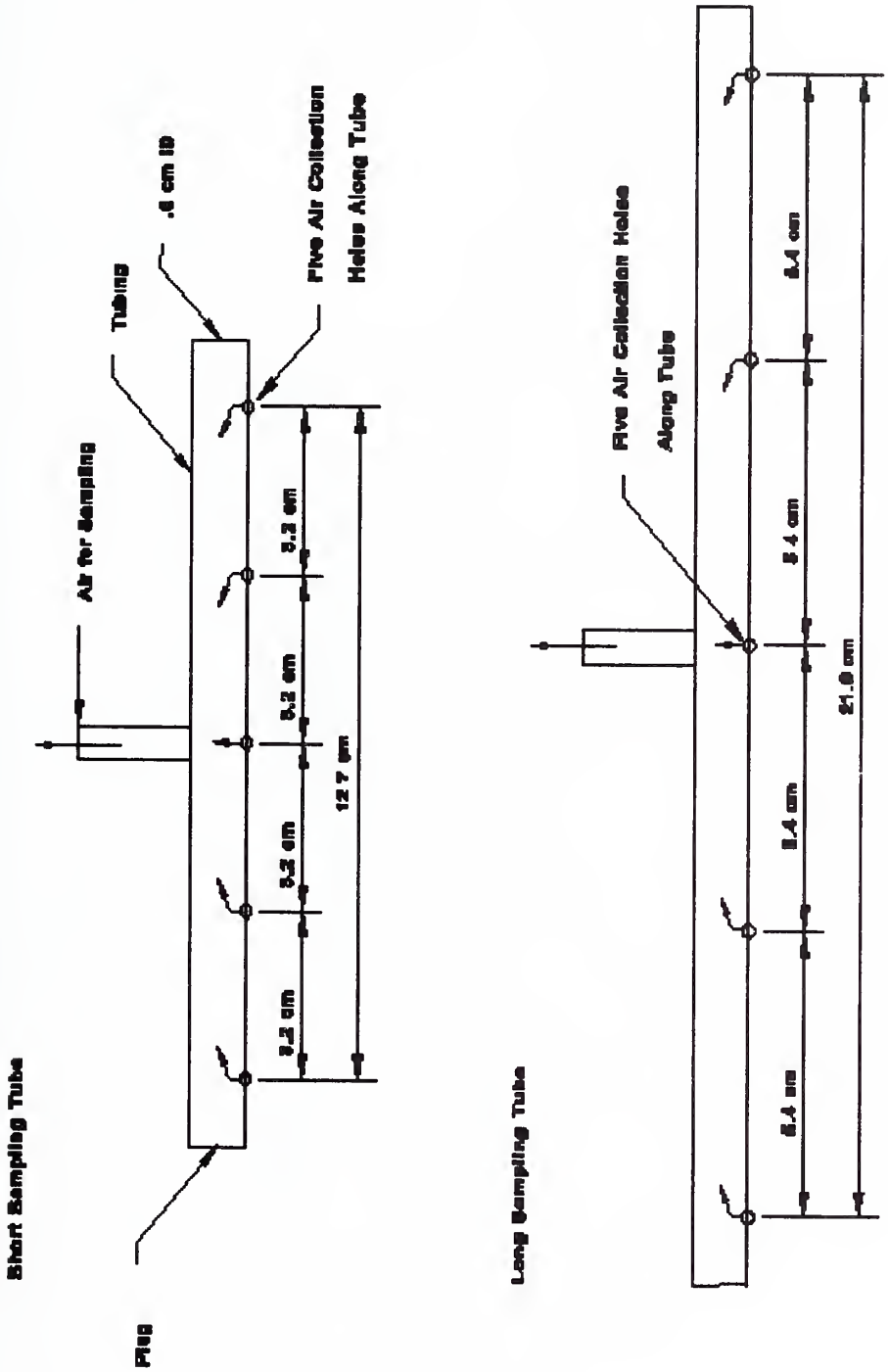


Figure 4.18 Geometry of Sampling Tube Holes.

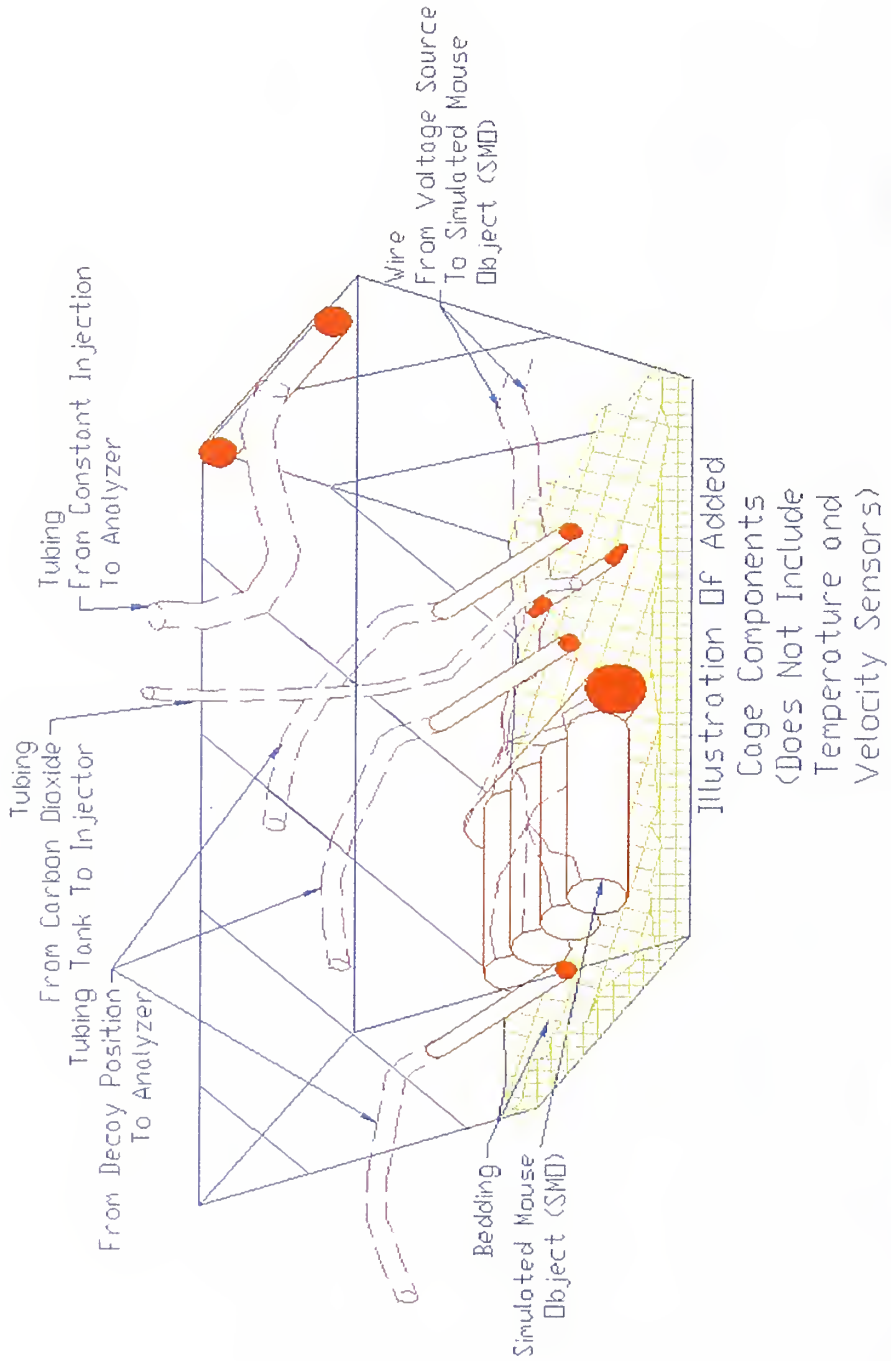


Figure 4.19 Model of the Cage with CO2 Injection/ Retrieval Location and SMO.

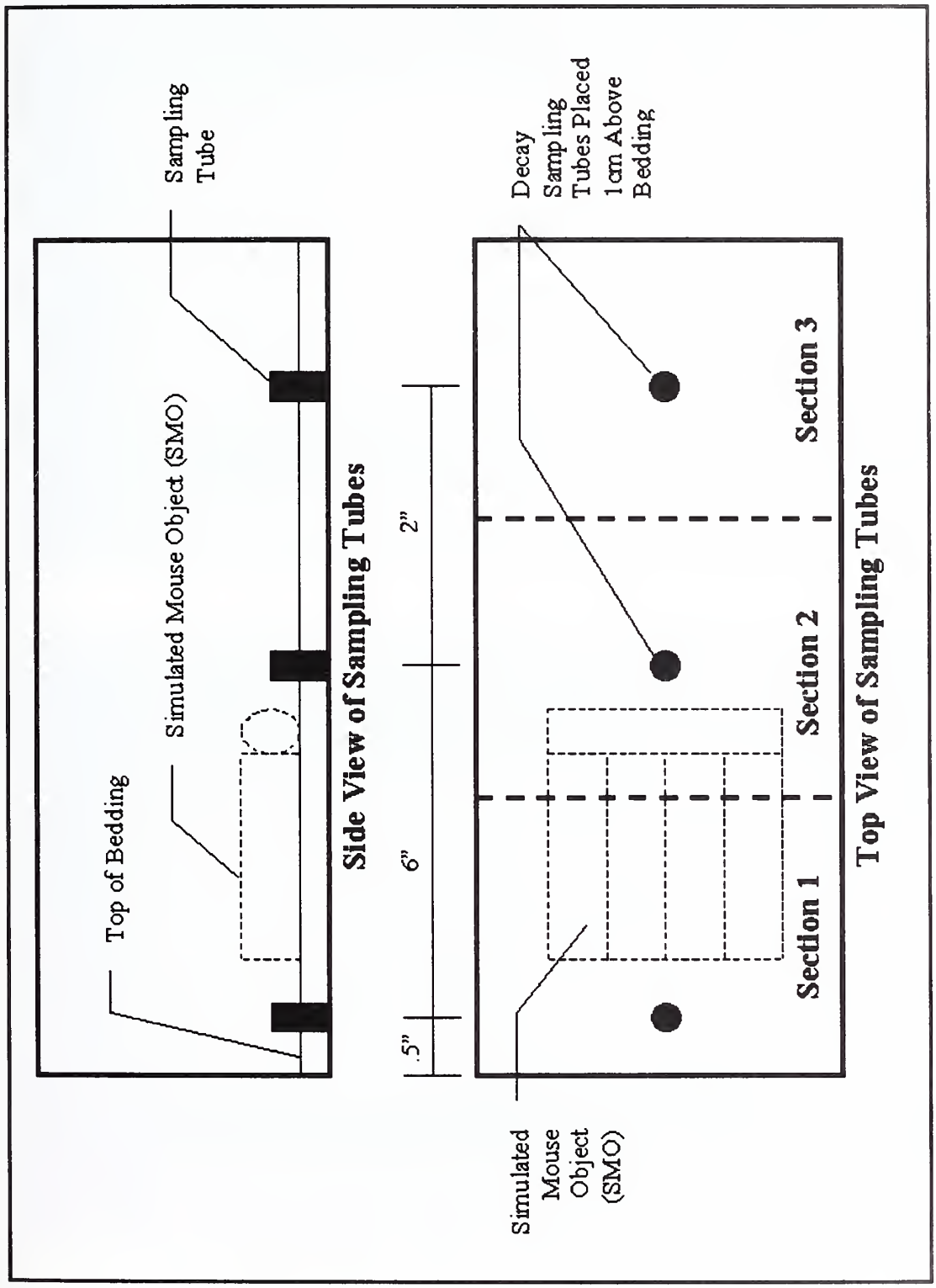


Figure 4.20 Decay Sampling Position.

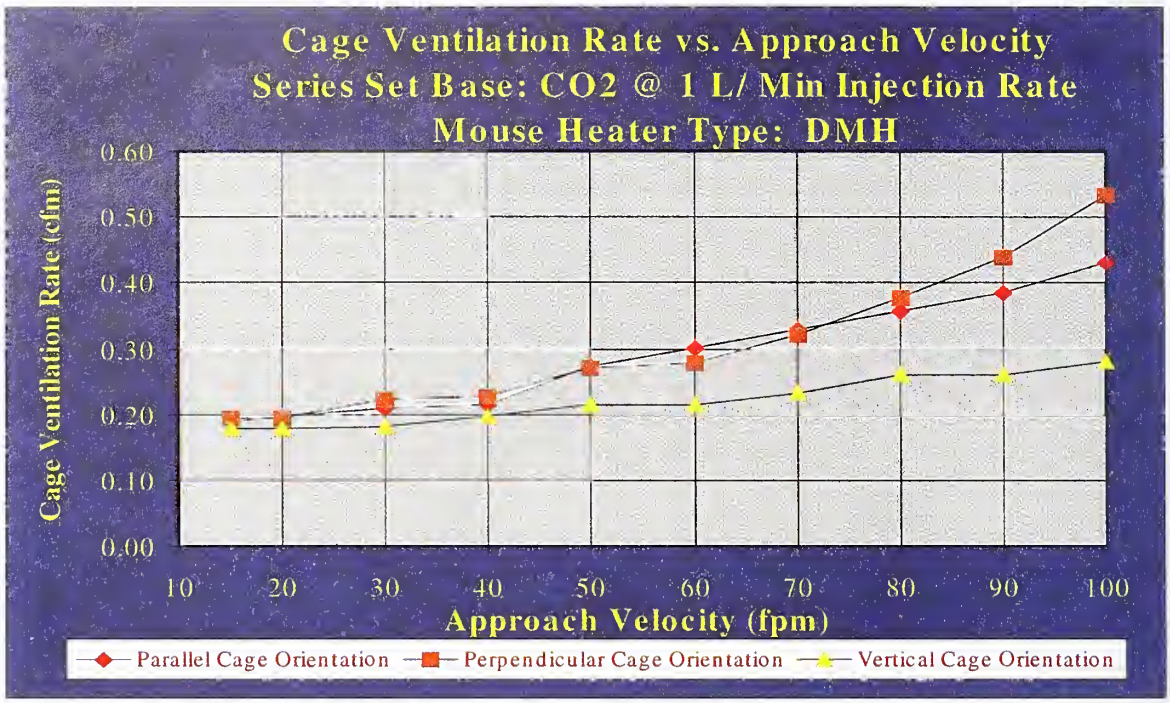


Figure 4.21 *Cage Ventilation Rate vs. Approach Velocity. Series Set Base.*

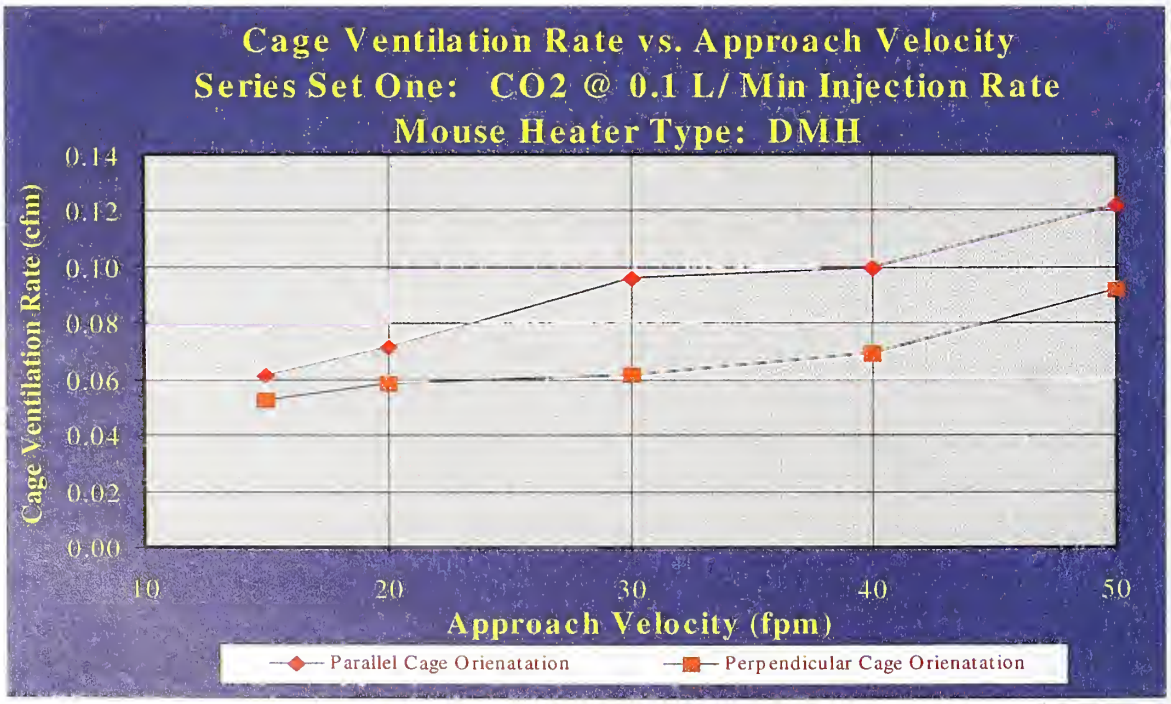


Figure 4.22 *Cage Ventilation Rate vs. Approach Velocity. Series Set One.*

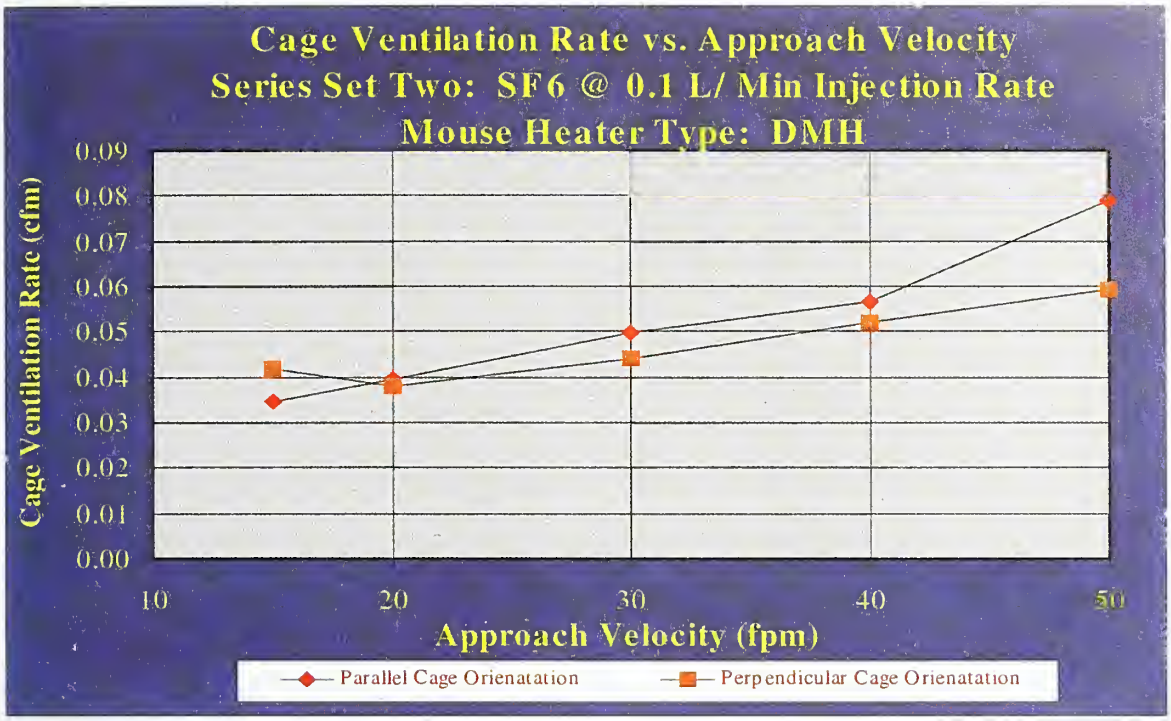


Figure 4.23 *Cage Ventilation Rate vs. Approach Velocity. Series Set Two.*

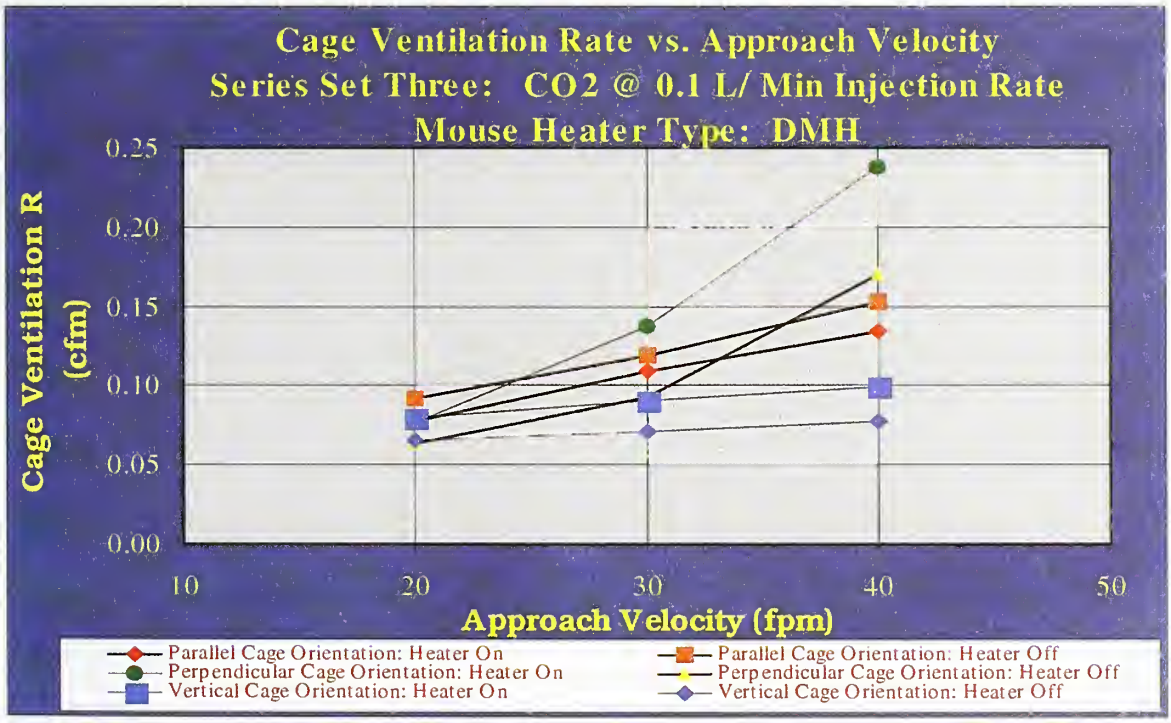


Figure 4.24 *Cage Ventilation Rate vs. Approach Velocity. Series Set Three.*

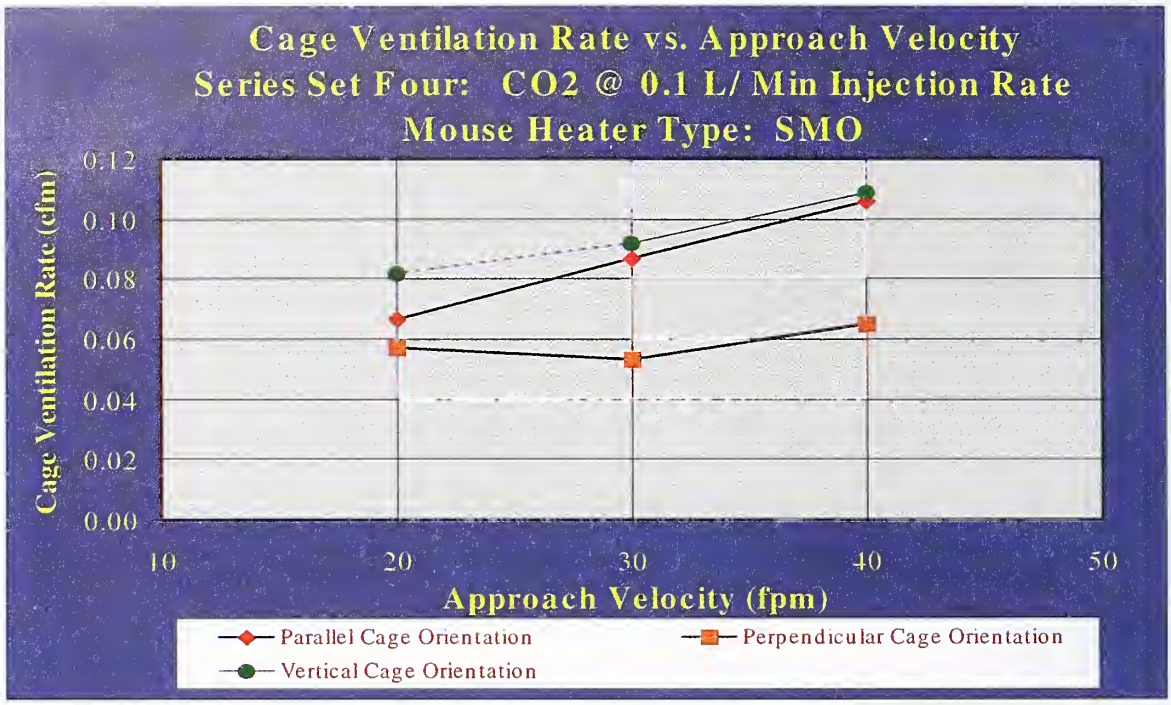


Figure 4.25 *Cage Ventilation Rate vs. Approach Velocity. Series Set Four.*

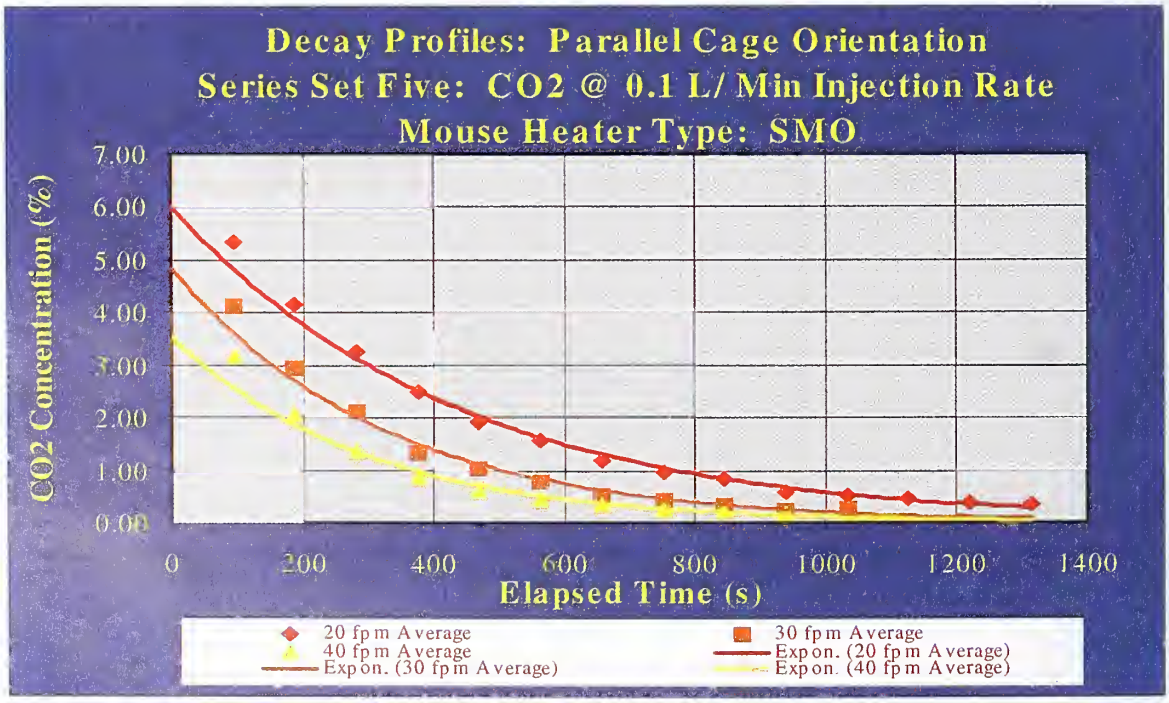


Figure 4.26 *Decay Profiles: Parallel Cage Orientation. Series Set Five.*

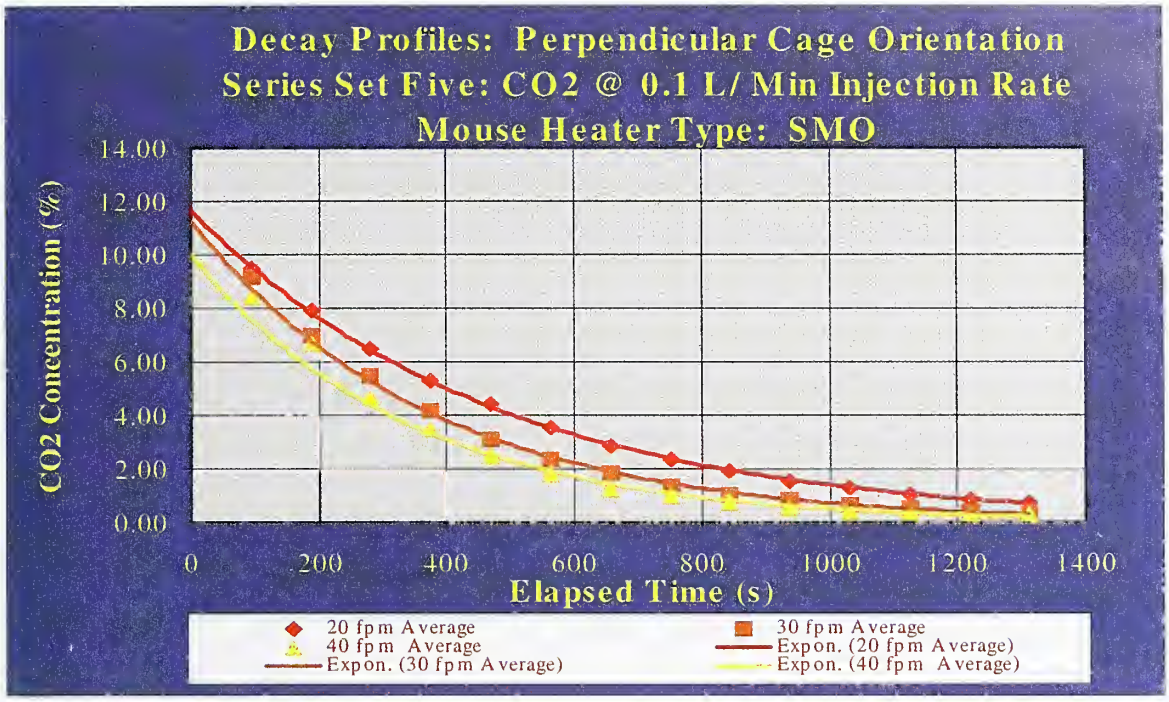


Figure 4.27 *Decay Profiles: Perpendicular Cage Orientation. Series Set Five.*

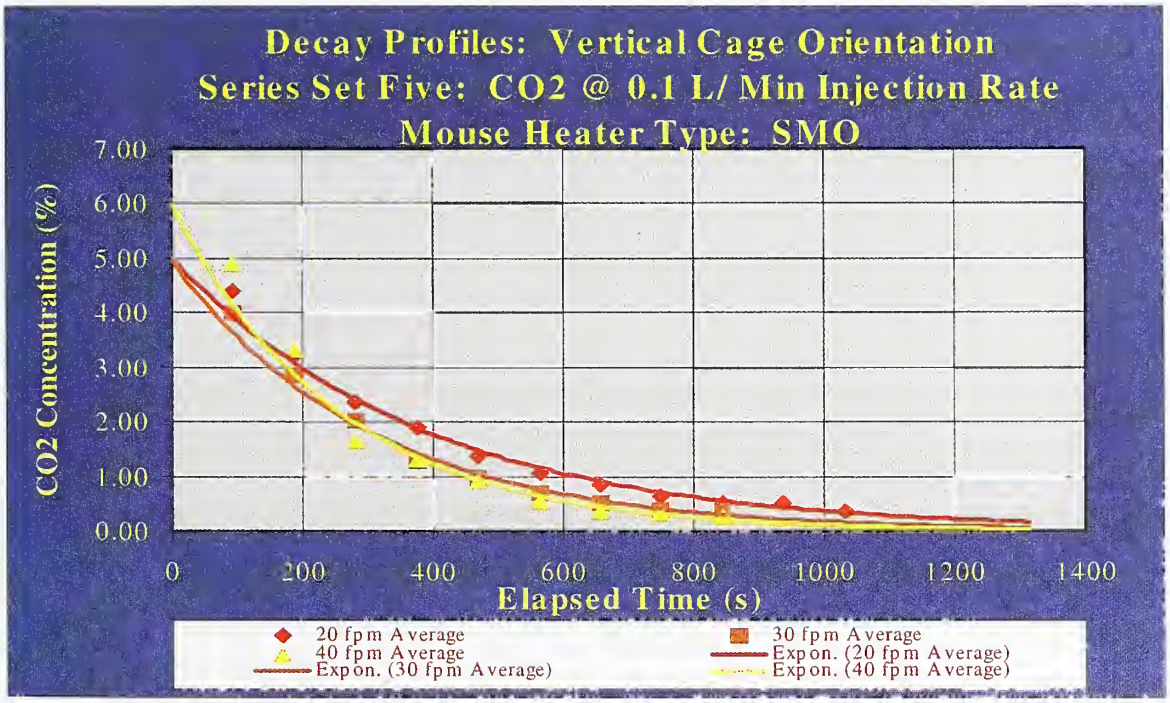


Figure 4.28 *Decay Profiles: Vertical Cage Orientation. Series Set Five.*

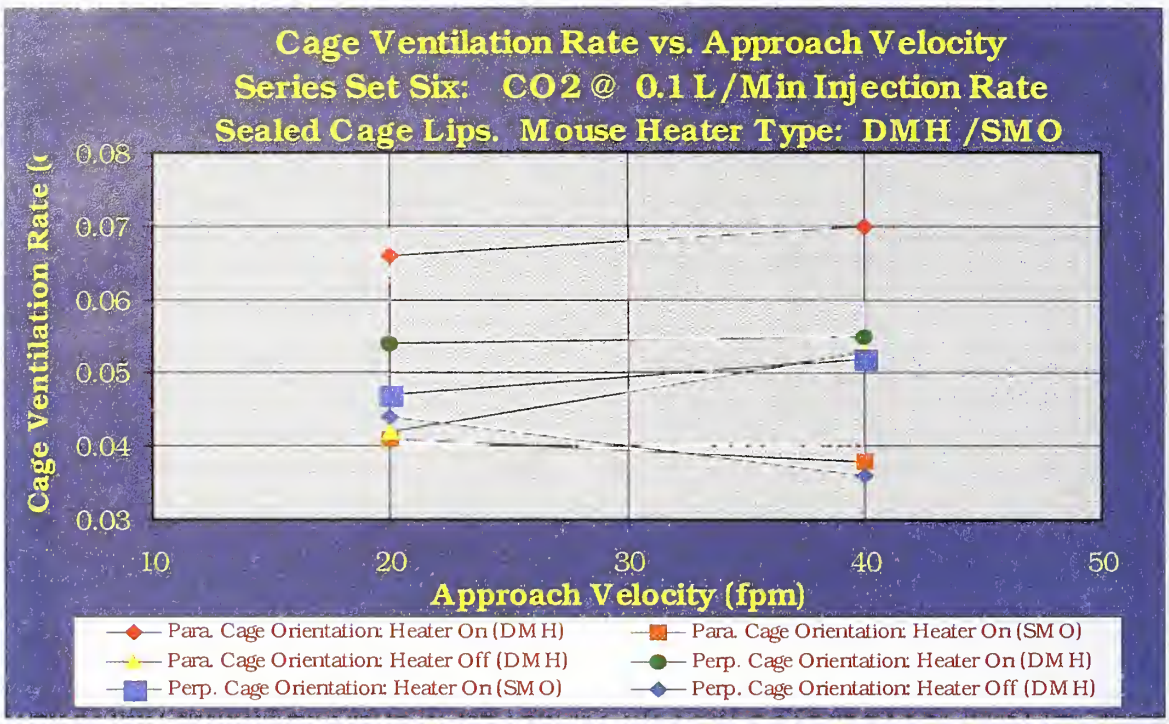


Figure 4.29 Cage Ventilation Rate vs. Approach Velocity. Series Set Six.

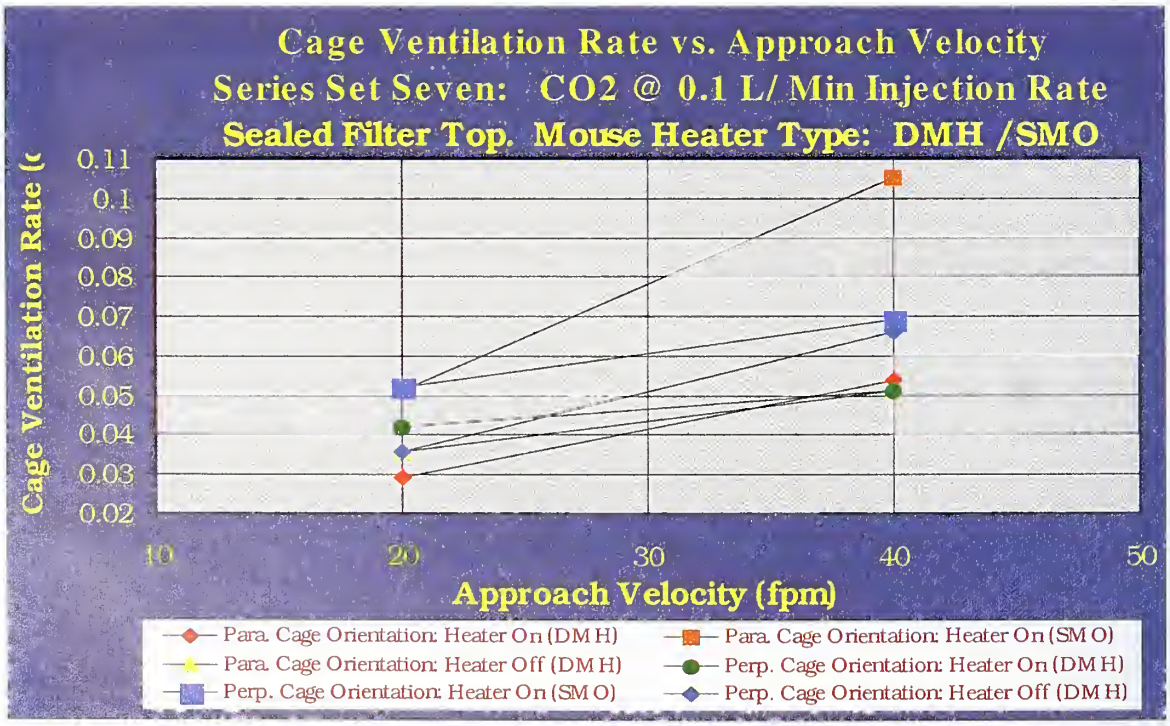


Figure 4.30 Cage Ventilation Rate vs. Approach Velocity. Series Set Seven.

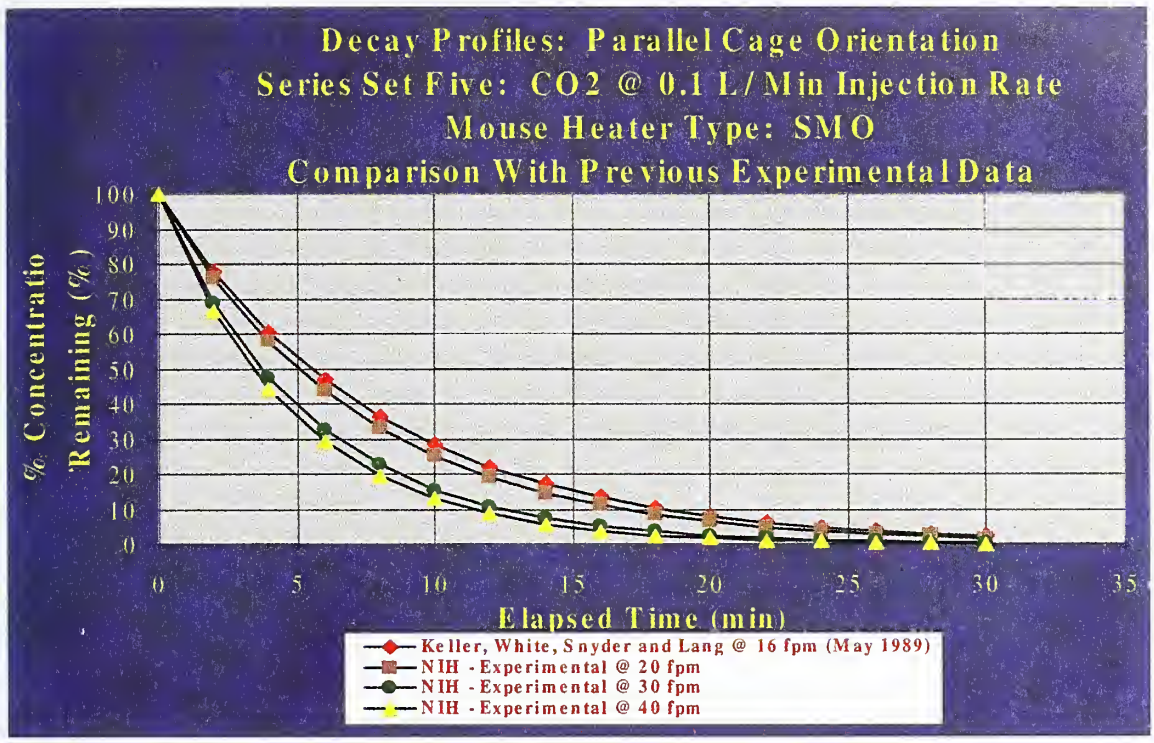


Figure 4.31 *Comparison of Series Set Five: Parallel Orientation Sampling Method Results and Results from Keller, White, Snyder and Lang (1989)*

4.1.2 CO_2, NH_3, H_2O and Heat Generation Measurements at Low and High Humidities

4.1.2.1 Introduction

This study was conducted at the Bioenvironmental Engineering Research Laboratory (BERL) and was intended to determine typical mass generation rates of CO_2, H_2O, and NH_3, and consumption of O_2 of mice in shoebox cages with bedding at two environmental relative humidities (35 percent and 75 percent). To determine the gas generation rates, animals and their cage habitat were placed within enclosed chambers (open-system calorimeters) with precisely controlled fresh air exchange rates. Cage bedding was not changed for longer than normal periods (10 days) to allow ammonia generating bacteria to develop within the bedding, that allowed us to obtain enough data to assess this time dependent process.

4.1.2.2 Mice and Husbandry Practices

Outbred mice (female, HSD-ICR, initial age of 4 weeks see figure 4.32) were placed in the shoebox cages for a 13-day period. The bedding type was hardwood (Beta chip) shavings. The cages and accessories were washed and sanitized prior to use using standard procedures for laboratory animal facilities. The number of mice per cage was the maximum allowable for the mouse weight and cage area (five mice/cage). The cages were housed in environmental chambers when not in the calorimeters. The environmental chambers and the chamber that the calorimeters were kept in were all approved for housing laboratory animals and were ventilated at 10-15 air changes per hour (ACH). The light period was 12 h light and 12 h dark; lights were turned on at 1:00 a.m. and off at 1:00 p.m. A white light and a blue light were on during the light period and only the blue light was on during the dark period. The light intensities of the light period and the dark period are presented in table 4.1.02. The mice received standard rodent diet and water *ad libitum.*

Table 4.1.03 Light intensities in mouse facilities

Calorimeter and Chamber	White and Blue Light On Light Intensities (lux)			White Light Off, Blue Light On Light Intensities (lux)		
Calorimeter 1	10			1		
Calorimeter 2	42			6		
Calorimeter 3	10			1		
Environmental Chamber #1 (RH 35 percent)	Top Shelf 25	Middle Shelf 7	Bottom Shelf 6	Top Shelf 2	Middle Shelf 1	Bottom Shelf 1
Environmental Chamber #2 (RH 75 percent)	Top Shelf 16	Middle Shelf 5	Bottom Shelf 4	Top Shelf 2	Middle Shelf 1	Bottom Shelf 1

The first three days after the mice arrived served as an acclimation period to allow the mice to adjust to their new surroundings and cage mates. The cages were kept at static conditions on

racks in two environmentally controlled chambers for acclimation. Both environmental chambers were kept at 24.0±1.5 °C (75.2±2.7 °F), but one was at 35±10 percent and the other at 75±10 percent relative humidity (RH). The temperature and relative humidity in each chamber were continuously monitored with hygrothermographs (Oakton, model 37250-00). Cage litter was changed after the 3-day acclimation period, that was just prior to the 10-day test period. After the experiment, the mice were euthanized in a container precharged with carbon dioxide.

4.1.2.3 Calorimeter design

Three indirect, convective calorimeters were used for this project (see figure 4.33). A brief introduction to the indirect calorimeter is given in appendix I: section 3.1. A flow diagram of the calorimeter is shown in figure 4.34. Air temperature, velocity, and relative humidity were controlled in each calorimeter. The calorimeter boxes were constructed from 6.4e-3m (¼") thick plexiglass and were 0.356m high x 1.07m long x 0.585m deep (14" x 42.13" x 23"). Clear plexiglass was used to allow observation of animals and to allow light into the calorimeter from the environmental chamber.

The entire front panel was removable to allow access of workers and to move mice in and out. The inside edges of the front panel were coated with vacuum grease to form a seal and were clamped on the calorimeter with 10 clamps around the perimeter. A recirculation pipe, 200mm diameter plexiglass tube, exited from one side of the calorimeter box, went up and over the calorimeter, and attached to an in-line fan on the other side of the calorimeter box. This air recirculation system allowed for the control of air velocity past the cages without affecting the fresh airflow exchange rate.

Air Temperature Control

The calorimeter box and air recirculation system were completely sealed to maintain the gas balance. Therefore, heat generated within the calorimeter had to transfer through the box or tube surfaces. To enhance this heat transfer process, all three calorimeters were placed within an environmental chamber that was operated at a lower temperature than the calorimeter air temperature. Also, a plastic duct, which served as a heat exchanger, was placed around the outside portion of the air recirculation tube and conditioned air was forced between that duct and the air recirculation tube to create a heat exchange system. One separate air conditioning/heating unit per calorimeter was placed outside the environmental chamber. Air from the tube heat exchange surface was recirculated through these units to control the temperature of the air passing through the heat exchanger and, thus, the amount of heat leaving or entering the heat exchanger. This heat exchange system, plus a 150W electric heater bar placed in the air recirculation tube, allowed for precise control of air temperature entering the calorimeter boxes.

The heat exchanger, air conditioners, and heaters were controlled with a microprocessor PID temperature controller (Omega model CN9122A). Each calorimeter was individually controlled. Temperatures within the calorimeters were sensed with one type T thermocouple placed in the

center of the calorimeter box in front of the cages. The thermocouples were read with a Campbell data logger (model 21X). Air temperature was set at 24.0±1.5 °C (75.2±2.7 °F).

Figure 4.32 *Outbred Mice Female – HSD – ICR.*

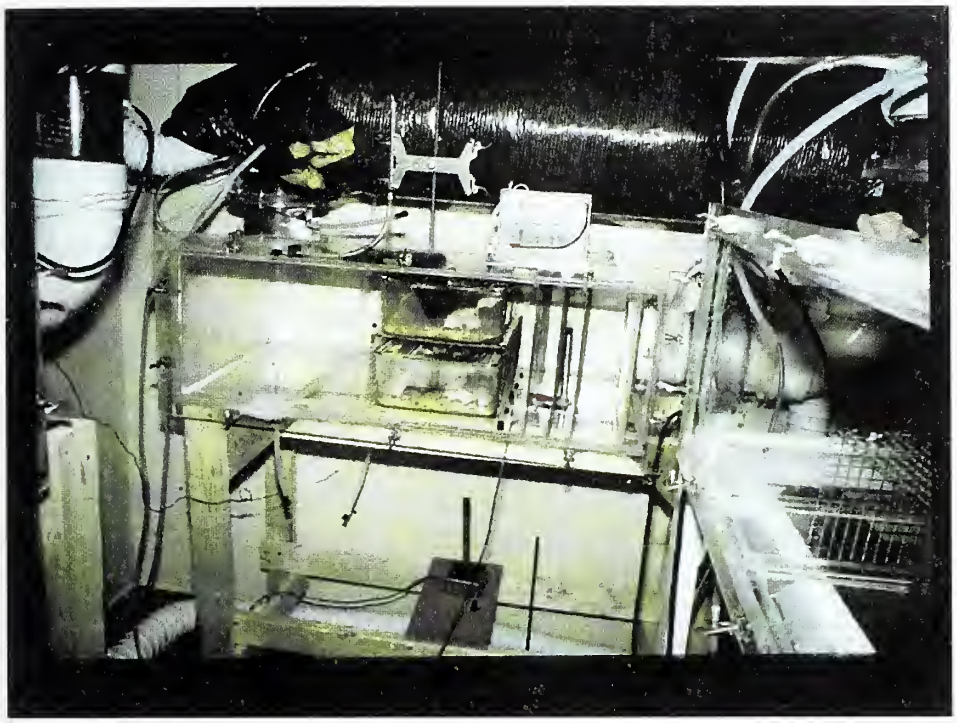


Figure 4.33 An Indirect Convective Calorimeter

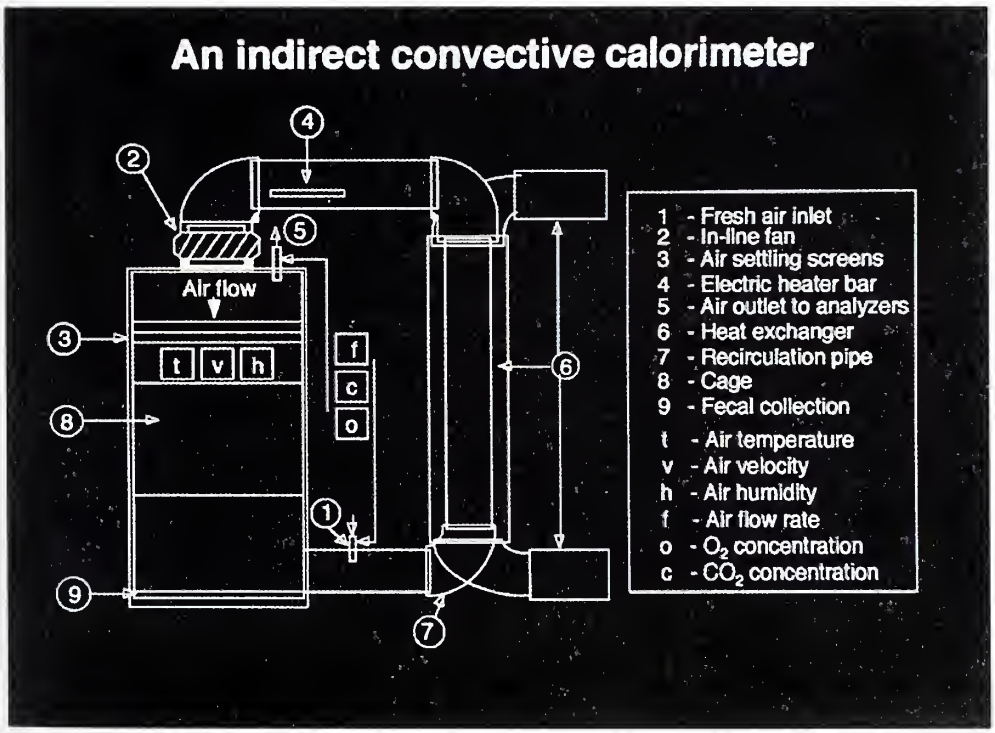


Figure 4.34 Flow Diagram - Indirect Convective Calorimeter

Air Velocity Control

Air moved horizontally through the calorimeter so the movement was from front to back along the animal cages. Air movement was created by recirculating air through the air recirculation tube described previously. The airflow rate through the recirculation fan was controlled by adjusting the fan speed with a voltage controller. There was a square air diffuser at the air entry that distributed the air around the calorimeter cross-section. To further improve the uniformity of airflow across the cross-section, an air settling means was placed after the diffuser and before the animal cages, consisting of three perforated stainless steel sheets with 60 percent, 40 percent, and 30 percent open areas. To ensure that there was a uniform profile of air velocities approaching the animal cages, a 3 x 5 grid of air velocity measurements was taken between the air settling means and before the cages with a TSI air velocity meter (model 8738). The average air velocities approaching the mouse cages were set at 0.25±0.05 m/s (50±10 fpm) prior to each test (see appendix I: section 3.2.1 and 3.2.2 for calibration data).

Air Humidity Control

Relative humidity of the air within the calorimeters was controlled by three systems: 1) fresh air exchange, 2) desiccant drying system, and 3) humidification system.

1) Fresh air exchange (ventilation)–was provided to each calorimeter for several reasons: a) maintain appropriate O_2, CO_2, and NH_3 levels, b) remove moisture and help maintain appropriate relative humidity, and c) provide sample of air for gas analysis. Air was removed from the air entry part of the 0.20m (8") diameter air recirculation tube and passed through a Gilmont Instruments model GF1300 airflow meter (accuracy = ± 2 percent of reading). These fresh air exchange flow meters were calibrated prior to each test against a 1-liter bubble airflow meter (see appendix I: section 3.2.5 and 3.2.6 for calibration data). The air then flowed to a diaphragm pump that had a 500mL beaker in line to dampen the oscillation from the pump. Airflow rate was controlled by an air bypass system with a needle valve. Air flowed from the pump system to the gas analysis instruments, that were located in an adjacent environmental chamber.

Air drawn out of the calorimeters was precisely measured and used as flow rate in the O_2 consumption and CO_2 production calculations. A slight negative pressure was maintained within the calorimeters. This negative pressure would draw in the same amount of fresh air from the surrounding environmental chamber as was removed by the pump. A planned air inlet (8-mm diameter hole) was placed in the inlet part of the air recirculation tube, but some fresh air would have entered through unplanned inlets (leaks). Since the entire calorimeter was at a negative static pressure and a certain amount of air had to enter the calorimeter anyway, the leaks did not create a problem.

The air that entered the planned inlet passed first through a container of desiccant to remove its moisture. This fresh air was passed through a 30x10 cm desiccant cylinder filled with approximately 3500g of 100 percent $CaSO_4$, #8 mesh granules, to help control calorimeter relative humidity (see figure 4.34).

2) Desiccant drying system–A separate air humidity control system was developed to remove moisture from the calorimeter air. To accomplish this, calorimeter air was recirculated through a desiccant drying system. The dehumidification system consisted of two diaphragm air pumps (approximately 10 L/min each) that pulled air from the calorimeter, passed it through a 0.30 x 0.10 m (12" x 4") desiccant cylinder filled with 100 percent $CaSO_4$, then returned the air back into the calorimeter (see figure 4.34; Dehumidification System). As the air passed through the desiccant, it effectively removed all of the moisture. The relative humidity exiting the bottom of the drying container was measured to be 0 percent with a Tri-Sense temperature/humidity meter (model 37000-00). The air pumps were operated manually based on the relative humidity in the calorimeter, which was sensed electronically with General Eastern (model RH-5-V) humidity transducers. The relative humidity sensors in each of the calorimeters and in the environmental chamber housing the calorimeters were calibrated prior to each 10-day run with a psychrometer. The signal from these sensors was collected on a Keithley Metrabyte DAS-8/PGA data acquisition system connected to an IBM compatible PC. The signals were analyzed with Keithley Metrabyte VIEWDAC software. After each calorimeter test, the desiccant was dried in an oven at 220 °C for 1.5 h and reused.

3) Humidification system–For the high humidity calorimeters, water was added to the air as needed to control relative humidity by passing the recirculation air over an evaporative pad (see detailed operating procedure for humidification system in appendix I: section 3.3). Water was placed in a graduated cylinder above each calorimeter and flowed through a tube to an electric solenoid, then into the calorimeters to drip into an evaporative pad (figure 4.34; Humidification System). The solenoid valves were opened and closed manually based on the relative humidity readings (see detailed operating procedure for relative humidity measurements in appendix I: section 3.3).

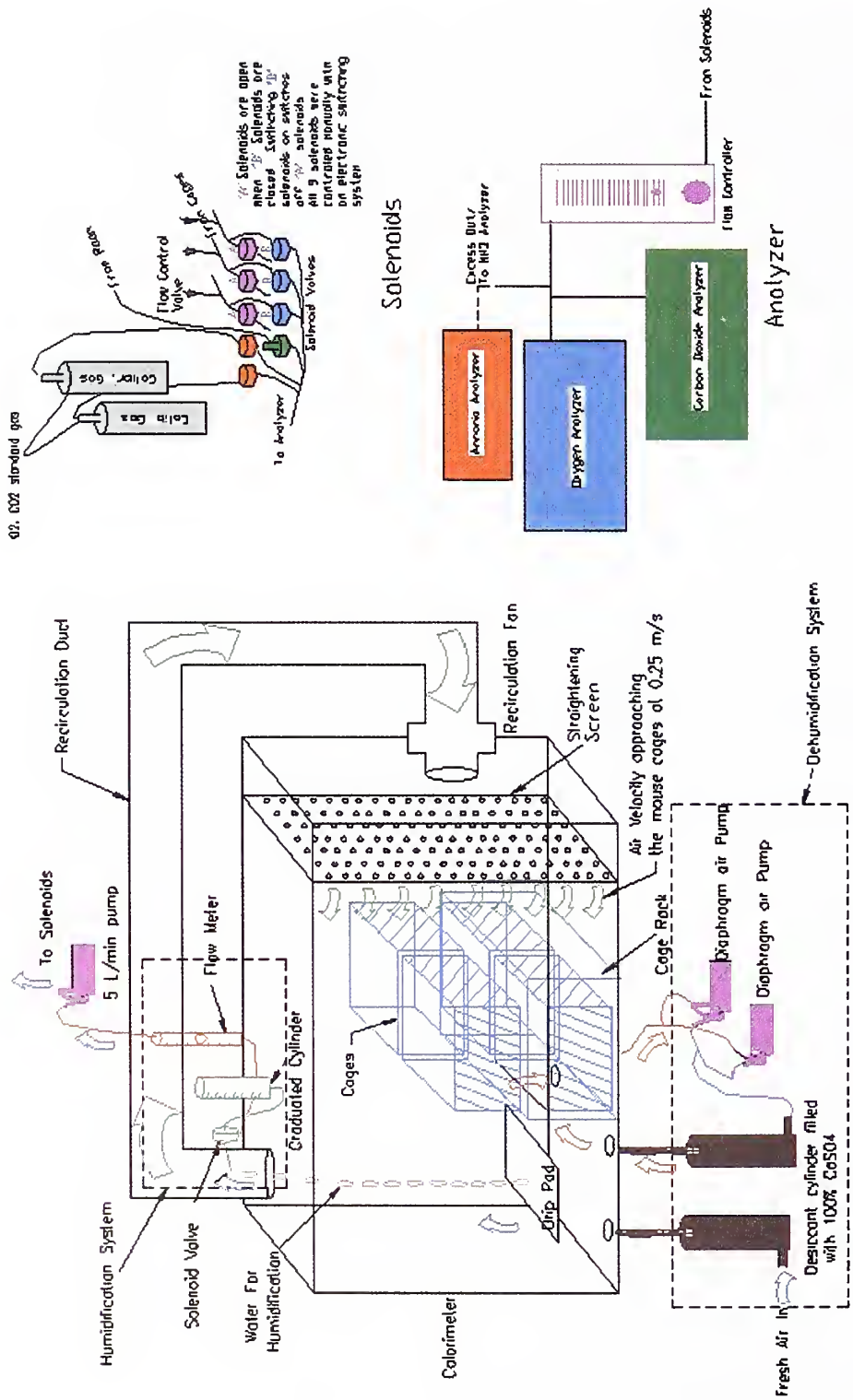


Figure 4.35 Experimental Apparatus for Mass Generation Rates of Ammonia in Mouse Cages at Low and High Relative Humidities.

Oxygen, Carbon Dioxide, and Ammonia Analysis

Air flowed through a manually controlled solenoid valve switching system that controlled airflow to the O_2 and CO_2 analysis instruments (Beckman model OM-11 and LB-2, respectively). Air was analyzed from six sources—the three calorimeters, the environmental chamber that housed the calorimeters, and two standard gases. Each source was connected to a separate solenoid valve that directed air through the O_2 and CO_2 analyzers and either stopped airflow (standard gases) or redirected it into the outside room (calorimeter and chamber air). All of the solenoid valves were controlled manually. Certified standard gases (Matheson) were used to set the ranges of O_2 and CO_2 that were to be analyzed. Standard gas #1 was certified to have approximately 17.5 percent O_2 concentration and 0.55 percent CO_2 concentration. Standard gas #2 was certified to have 18.9 percent O_2 concentration and 1.58 percent CO_2 concentration. Output from the gas analyzers was continuously recorded on a strip chart recorder. Ammonia concentration of the sample air was measured with an ammonia gas detector (PhD model 1600W/1633, Biosystems, Inc.) that was calibrated to ammonia standard gases at 52.7 ppm. During the second test, calorimetric tubes (MAS, No. 487339) were also used as a check for ammonia levels.

Calibration of Calorimeters

Prior to each of the 10-day test periods, the calorimeters were calibrated by burning an ethanol lamp in the calorimeters to determine their mean recovery ratios of CO_2 and O_2. This procedure also served as an integrated check on all components of the calorimeter and determined the overall accuracy of the calorimeter. An ethanol lamp was filled with absolute ethanol (EtOH) and placed on an analytical balance that had been leveled on a platform inside a calorimeter. The lamp was ignited, the calorimeter door was sealed shut. After the ethanol lamp established a steady burn rate, the change in weight (g/min) of the ethanol lamp was measured with a stopwatch over several 10-minute periods (ΔEtOH). Differences in percent O_2 content of air leaving the calorimeter (O_{2out}) was subtracted from O_2 content of air entering the calorimeter (O_{2in}) over the 10-minute periods (O_{2in}–O_{2out}). The same procedure for CO_2 analysis was simultaneously recorded (CO_{2out}–CO_{2in}). Accuracy, recovery, and calibration values for each calorimeter were obtained by comparison of respiratory quotient [RQ = (CO_2 produced)/(O2 consumed)] and recovery of gases obtained from the ΔEtOH, ΔO_2 percent, and ΔCO_2 percent measurements. Calibration had RQ ranges from 0.64 to 0.81 in test 1. The accuracy of O_2 and CO_2 recovery ratio ranged from 83 percent and 94 percent to 121 percent and 117 percent, respectively, in test 1. Calibration had RQ ranges from 0.67 to 0.81 in Test 2. The accuracy of O_2 and CO_2 recovery ranged from 88 percent and 101 percent to 112 percent and 114 percent, respectively, in test 2. Calibration results are presented in appendix I: section 3.2.7 and 3.2.8.

4.1.2.4 Experimental Procedure

There were two environmental relative humidity treatments (low and high relative humidity) and three replications per treatment so there were six experimental units. Since there were only three calorimeters, this experiment was divided into two time periods. During test 1 (Oct. 18, 1997 to Oct. 27, 1997), two experimental units were at the 35 percent relative humidity treatment and one experimental unit was at the 75 percent relative humidity treatment. During test 2 (Dec. 13, 1997 to Dec. 22, 1997), two experimental units were at the 75 percent relative humidity treatment and one at the 35 percent treatment. When the mice first arrived, they were randomly assigned to 15 cages, then some adjustments were made to equalize average mouse weight among the cages. Only 12 cages were used in the tests, but extra mice were ordered to replace experimental animals if problems occurred. None of the extra mice were used. During test 1, 10 cages were randomly assigned to the 35 percent relative humidity treatment and five cages to the 75 percent relative humidity treatment. During test 2, 10 cages were assigned to the 75 percent and 5 cages to the 35 percent relative humidity treatments. The assignment of cages is shown in appendix I: sections 3.2.9 and 3.2.10.

After the 3-day acclimation period, there was a 10-day test period when the mice were placed in the calorimeters for 10 hours each day where the measurements were taken (see standard operating procedures in appendix I: section 3.3). During the rest of the day, the mice were kept in their respective environmental chambers. The same four cages were always randomly assigned to a different calorimeter each day and were an experimental unit (the randomized assignments are in appendix I: section 3.2.9 and 3.2.10). At the morning of every day of the tests, the mice, feed, water, and litter were weighed separately. Four cages with five mice each were placed in each calorimeter for a total of 20 mice in each calorimeter. The three calorimeters were operated at the same temperature (24.0±1.5 °C (75.2±2.7 °F). Data were collected three times during the photophase (approximately at 10:40, 11:20 and 12:00 a.m.) and three times during the scotophase (approximately at 3:15, 4:00 and 4:40 p.m.). Since the lights were shut off at 1:00 p.m., half of the data were obtained during the daily photophase and half during the scotophase, so effects of light could be determined.

The calorimeters were in the horizontal position so airflow approached the front of the cages (see figure 4.34). The four cages were positioned on two levels (as in a cage rack). The calorimeter static pressure was kept negative. The fresh air exchange rates for the calorimeters varied from 5 to 9.3 L/min. Fresh airflow rates were increased over the 10-day test period to keep ammonia levels low. After the mice were placed in the calorimeter and also after the lights were turned off, a dehumidification system was manually turned on for approximately one hour for the low humidity calorimeters to reduce the humidity. The dehumidification system was only operated for about one hour then the gas levels were allowed to stabilize for around two hours before readings were taken. Weights of the desiccant cylinders were determined at the start and end of each daily experiment so water balances could be calculated. At the beginning of each daily experiment, the cylinders were emptied and refilled with recharged desiccant. Water production was measured based on water added to calorimeter, different weights of desiccant cylinders in

the dehumidification system, and relative humidity and temperature readings of the calorimeters and chamber.

4.1.2.5 Recovery Ratio of CO_2 and O_2 Calculation.

Assumptions: EtOH has a molecular weight of 46.0694, 22.414 liters (L) of gas per mole, and 4.9 Kcalories of energy per L O_2 consumed, and 7.1 Kcal/g of heat of combustion.

According to:

$$C_2H_6O + 3O_2 \rightarrow 2CO_2 + 3H_2O + \text{Energy} \quad (4.5)$$

$$RQ = \frac{2CO_2}{O_2} = 0.67 \quad (4.6)$$

Equation to calculate CO_2 generation rate and O_2 consumption rate from sample air:

$$P_{CO2} = \frac{(CO_{2out} - CO_{2in}) \times M}{100} \quad (4.7)$$

$$P_{O2} = \frac{(O_{2in} - O_{2out} \times M}{100} \quad (4.8)$$

Where:

P_{CO2}, P_{O2}	CO_2 generation rate and O_2 consumption rate, L/min.
CO_{2out}, O_{2out}	CO_2 concentration and O_2 concentration of sample air, percent.
CO_{2in}, O_{2in}	CO_2 concentration and O_2 concentration of chamber air, percent.
M	Air exchange flow rate, L/min.

Respiratory quotient (RQ):

$$RQ = \frac{P_{CO2}}{P_{O2}} \quad (4.9)$$

Equation to calculate CO_2 generation rate and O_2 consumption rate from burning EtOH:

$$EtOH = \frac{D \times 22.414 \times F}{10 \times 46.069} \quad (4.10)$$

where:

EtOH	CO_2 generation rate and O_2 consumption rate from burning EtOH, L/min
D	Burning EtOH weight in 10 minutes, g
F	Factor: 2 for CO_2 and 3 for O_2.

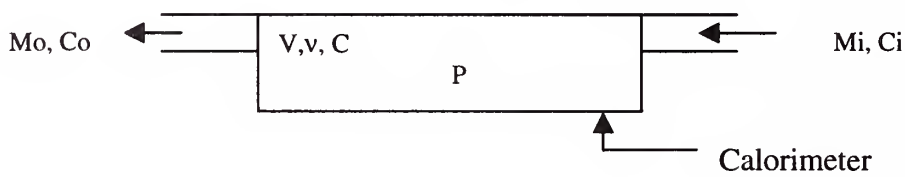
Equation to calculate recovery ratio:

$$\text{Recovery ratio} = \frac{P}{EtOH} \tag{4.11}$$

where:

P	CO_2 generation rate and O_2 consumption rate from sample air, L/min

4.1.2.6 Mass Generation Rate Calculation



where:

mi, mo	Fresh air flow rate, kg/s
Ci,C, Co	Ammonia concentration, mg/kg
V	Volume of the calorimeter, m^3 (0.225 m^3)
v	Specific volume of air, m^3/kg
P	Ammonia production rate, mg/s

$$\frac{V}{v}\frac{dC}{dt} = miCi + P - moCo \tag{4.12}$$

Since mi = mo = m and C=Co, by solving the above equation we get the following result:

$$C = Ci + \frac{P}{m}(1 - e^{-\frac{mv}{V}t}) \tag{4.13}$$

When the time goes to infinity, the calorimeter reaches the stable state, where the concentration is Ci + P/m. If we let τ=V/mv, then when t=3τ, the concentration will reach 95 percent of the stable state value. We ran our test mostly at 5 L/min flow rate. The volume of the calorimeter is 225 L. So τ is 45 minutes and after 135 minutes, the concentration will reach 95 percent of its stable value. We measured the ammonia concentration at the stable state.

So:

$$C = Ci + \frac{P}{m} \tag{4.14}$$

With the units transfer:

$$P = 0.7598 \times 0.001 \times 6 \times \frac{(C - Ci) \times m}{W_m} \tag{4.15}$$

where:

P	Ammonia generation rate, g/hr/100g of mice.
C	Ammonia concentration in the calorimeter, ppm.
Ci	Ammonia concentration in the chamber, ppm.
m	Fresh air flow rate, L/min.
W_m	Mice weight in one calorimeter, g.

Using the same general equation to calculate carbon dioxide generation rate and consumption rate of O_2.

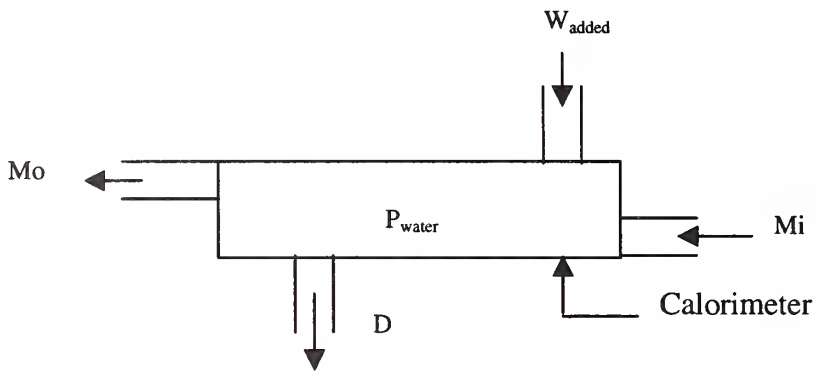
$$P = 1.964 \times 60 \times \frac{(C - Ci) \times m}{W_m} \tag{4.16}$$

where:

P	Carbon dioxide generation rate or oxygen consumption rate, g/hr/100g of mice.
C	Carbon dioxide concentration in the calorimeter, percent.
Ci	Carbon dioxide concentration in the chamber, percent.

1L CO_2 = 1.964 g, 1L NH_3 = 0.7598 g, 1-mole = 22.414 liters of volume, and mole weight of NH_3 = 17.03.

4.1.2.7 Water Production Calculation



where:

P_{water}	Total water production, g/hr/100g of mice.
Mi	Leaking airflow rate, L/min.
Mo	Air exchange flow rate, L/min.
W_{added}	Water added to calorimeter, g.
D	Dehumidified water, g.

Equation to calculate water from air pumped out:

$$P_{out} = \frac{R_a \times M_o \times 1.1614 \times 6}{W_m} \tag{4.17}$$

where:

P_{out}	Water production from pumped out air, g/hr/100g of mice.
R_a	Humidity ratio g moisture /kg dry air in calorimeter, g/kg.
W_m	Mice weight in calorimeter, g.
1.1614 x 6	Coefficient to convert units.

Equation to calculate water entering calorimeter through air leaking in:

$$P_{in} = \frac{R_r \times M_i \times 1.1614 \times 6}{W_m} \tag{4.18}$$

where:

P_{in}	Water gain due to air leakage, g/hr/100g of mice.
R_r	Humidity ratio, g moisture/ kg dry air in chamber, g/kg.

Equation to calculate water added in caloirmeter (P_{added}, g/hr/100g of mice) over the10 hr test period:

$$P_{added} = \frac{W_{added}}{10} \times \frac{100}{W_m} \tag{4.19}$$

Equation to calculate water removed by dehumidification system (P_d, g/hr/100g of mice) over the10 hr test period:

$$P_d = \frac{D}{10} \times \frac{100}{W_m} \tag{4.20}$$

The total water production was summed:

$$P_{water} = P_{out} - P_{in} + P_d - P_{added} \tag{4.21}$$

4.1.2.8 Data Analysis and Results

4.1.2.8.1 Preliminary Data Tabulation, Collection and Analysis

All data referred to in this section are listed in tabulated and graphical form in appendix I.

In this experiment, data were collected three times during the photophase and three times during the scotophase every day, and this data is reported in appendix I: section 3.4.1 under raw data for test 1 and test 2. The averages of the three data points taken in the photophase and the scotophase each day are reported in appendix I: section 3.4 under individual calorimeter data for NH_3, CO_2, and O_2 concentration for test 1 and test 2. The mass generation rates were calculated based on these data.

The relative humidity sensors in each of the calorimeters and chamber sensed relative humidity every five minutes over the 10 hr test period each day and values are reported in appendix I: section 3.4 under relative humidity data for test 1 and test 2. The average values of relative humidity and temperature in the calorimeters and chamber over the 10-hour test period were used to determine the humidity ratio value of the air (g moisture /kg dry air) from a psychrometric chart. This data were used along with data on water added by the humidification system and water removed by the dehumidification system to calculate water production rates which are reported in the appendix I: section 3.4 under water production data for test 1 and test 2.

The individual weight of mice, feed, water, and litter were determined every day of the tests and reported in appendix I: section 3.4 under raw weight data for test 1 and test 2. Mice weight in individual cages and cage group were calculated and reported in the appendix I: section 3.4 under mice weight for test 1 and test 2.

Since test 1 had two experimental units at the 35 percent relative humidity and test 2 had two experimental units at the 75 percent relative humidity, the average value of the two experimental units at 35 percent relative humidity in test 1, and the average value of the two experimental units at 75 percent relative humidity in test 2 are reported in the appendix I: section 3.4 under Average Gas Mass Generation Rates for All Experimental Units in Test 1 and Test 2.

The data for all experimental units in test 1 and test 2 were averaged for both relative humidity treatments and are presented in the appendix I: section 3.4 under average data for all experimental units from both test 1 and test 2. There were higher mass generation rates of ammonia in the high relative humidity treatment (RH 75 percent) than in the low relative humidity treatment (RH 35 percent). Mass generation rate of ammonia during scotophase is higher than during photophase at the same relative humidity treatment. Water production data have some variation in each day. Average value of water production data for the low relative humidity treatment was higher than for the high relative humidity treatment.

4.1.2.8.2 CO_2, NH_3 and H_2O Data Preparation for Use in CFD Simulations

The data were regrouped and reanalyzed for general usage, and for use in the CFD simulations performed later. As demonstrated in appendix I: sections 3.4.1.9 and 3.4.1.10, the levels of mass generation were higher for the dark (scotophase) period than they were for the light (photophase) period. Emphasis has therefore been placed on the scotophase results for the purposes of this study.

For each test, the cage group data were collected for each of the days in the experiment, and the actual level of cage relative humidity (RH) (expressed as a percentage) was tabulated with each of the measured generation rates. For example, in Tables 4.1.04 and 4.1.05 below, the NH_3 generation rates on a day-by-day basis for the groups of cages are collected together. These data can then be rearranged in terms of the Desired RH level, as demonstrated in Tables 4.1.06 and 4.1.07. Plotting the data contained in tables 4.1.06 and 4.1.07 in a graph, the relationship between the NH_3 level and the day number can be represented as a polynomial approximation for both the low RH level (Desired 30 – 35 percent RH) and the high RH level (Desired 75 – 80 percent RH), as shown in figure 4.36. The generation rate of NH_3 can be then be calculated by interpolation between the two polynomial approximations on a given day for a given level of cage RH. It should be noted that the average level of cage RH achieved in the Desired 30 – 35 percent RH experiments was 60.86 percent (compared with the environmental RH average of around 39 percent), while the average level of cage RH in the Desired 75 – 80 percent RH experiments was 79.69 percent. Therefore, the interpolated value is only wholly accurate between 61 percent and 80 percent cage RH. It is interesting to note that the generation of NH3 is clearly dependent on the level of cage RH. However, this is not the case for temperature. In particular, figure 4.37 shows that there is no clear relationship between the generation rate of NH3 and temperature: there is significant scatter in the experimental data.

The levels of H_2O and CO_2 can also be rearranged for general usage for the CFD work. **Note:** Although the values have been considered for the scotophase, the H2O measurements were not noted for the scotophase or photophase individually; as noted above, water production was considered over a 10 hr period each day, with measurements taken in 5-minute intervals. Tables 4.1.08 and 4.1.09 show the variation of H_2O and CO_2 on a day-by-day basis for test 1 and test 2 respectively, while Tables 4.1.10 and 4.1.11 rearrange the data according to the Desired RH level. figure 4.38. to 4.41 show the variations of H_2O and CO_2 with the day in the experiment for the low RH level (Desired 30 – 35 percent RH) and the high RH level (Desired 75 – 80 percent RH) experiments respectively (Note that the erroneous negative H_2O generation rate, highlighted in black in table 4.1.08, has not been included in figure 4.38). The plots show that, based on the degree of scatter in the experimental measurements, the levels of CO_2 and H_2O can be considered constant throughout the days of the experiment. In particular, the average values are as follows:

Low RH Level:

CO_2 generation rate (g /hr/ 100g BW)	=	9.35e-1 g/ hr/ 100g BW
H_2O generation rate (g /hr/ 100g BW)	=	7.84e-1 g/ hr/ 100g BW

High RH Level:

CO_2 generation rate (g /hr/ 100g BW) = 8.75e-1 g/ hr/ 100g BW

H_2O generation rate (g /hr/ 100g BW) = 8.78e-1 g/ hr/ 100g BW

It can be noted that the generation rates of H_2O and CO_2 do not change significantly with the RH level. We can therefore further reduce the generation rates to two numbers, which we can regard as constant irrespective of RH or day in the experiment.

CO_2 generation rate (g /hr/ 100g BW) = 9.05e-1 g/ hr/ 100g BW

H_2O generation rate (g /hr/ 100g BW) = 8.31e-1 g/ hr/ 100g BW

Table 4.1.04 Tabular Variation of RH, NH_3 and $NH_{3\,(max)}$ with Day: Test 1, Lights Off

Cage Group	Day	RH actual (percent)	NH_3 (g/ hr/ 100g BW)	$NH_{3\,(max)}$ (g/ hr/ 100g BW)
1-4 (Desired RH = 30 – 35 percent)	1	71.3	4.69E-04	5.87E-04
	2	66.1	5.44E-04	7.32E-04
	3	70.4	8.30E-04	9.96E-04
	4	62.9	1.26E-03	1.52E-03
	5	61.4	0.00E+00	2.07E-04
	6	54.4	1.34E-03	1.38E-03
	7	52.6	1.96E-03	2.22E-03
	8	58.4	1.86E-03	2.06E-03
	9	61.4	4.31E-03	4.55E-03
	10	57.1	5.62E-03	6.28E-03
5-8 (Desired RH = 75 – 80 percent)	1	69.7	3.88E-04	4.76E-04
	2	84.8	5.23E-04	6.49E-04
	3	83.8	1.46E-03	1.91E-03
	4	78.2	3.73E-03	4.11E-03
	5	77.7	4.06E-03	4.68E-03
	6	79.6	4.27E-03	4.48E-03
	7	76.3	5.22E-03	5.39E-03
	8	81.1	7.30E-03	7.65E-03
	9	83.4	6.60E-03	6.70E-03
	10	80.6	5.02E-03	5.22E-03
9-12 (Desired RH = 30 – 35 percent)	1	68.0	5.67E-04	6.38E-04
	2	67.7	5.24E-04	7.59E-04
	3	62.8	6.99E-04	8.39E-04
	4	66.2	1.23E-03	1.44E-03
	5	56.8	1.29E-03	1.42E-03
	6	55.5	1.59E-03	1.65E-03
	7	62.4	2.59E-03	2.69E-03
	8	54.1	2.04E-03	2.24E-03
	9	60.2	4.71E-03	4.78E-03
	10	60.5	3.43E-03	4.01E-03

Table 4.1.05 Tabular Variation of RH, NH_3 and $NH_{3\,(max)}$ with Day: Test 2, Lights Off

Cage Group	Day	RH actual (percent)	NH_3 (g/ hr/ 100g BW)	$NH_{3\,(max)}$ (g/ hr/ 100g BW)
1-4 (Desired RH = 30 – 35 percent)	1	69.7	9.21E-05	1.11E-04
	2	59.6	0.00E+00	0.00E+00
	3	62.6	5.30E-05	1.06E-04
	4	63.7	2.89E-04	3.06E-04
	5	64.4	5.94E-04	6.29E-04
	6	58.0	1.05E-03	1.10E-03
	7	64.0	1.02E-03	1.41E-03
	8	50.3	-	-
	9	50.6	3.68E-03	4.66E-03
	10	52.4	2.75E-03	3.82E-03
5-8 (Desired RH = 75 – 80 percent)	1	73.9	1.28E-04	1.64E-04
	2	83.5	3.69E-05	5.53E-05
	3	79.5	9.19E-05	1.10E-04
	4	83.8	3.71E-04	4.24E-04
	5	86.9	2.15E-03	2.22E-03
	6	75.7	6.75E-03	7.19E-03
	7	87.5	8.16E-03	8.91E-03
	8	77.3	1.00E-02	1.04E-02
	9	75.2	1.39E-02	1.45E-02
	10	77.7	1.16E-02	1.21E-02
9-12 (Desired RH = 75 – 80 percent)	1	74.3	1.26E-04	1.61E-04
	2	80.4	3.53E-05	5.29E-05
	3	84.4	7.00E-05	1.05E-04
	4	79.4	5.29E-04	6.35E-04
	5	82.8	3.35E-03	3.54E-03
	6	81.1	6.38E-03	6.74E-03
	7	76.5	8.99E-03	9.36E-03
	8	76.8	1.14E-02	1.19E-02
	9	77.6	1.18E-02	1.23E-02
	10	81.0	1.03E-02	1.14E-02

Table 4.1.06 Tabular Variation of RH, NH_3 and $NH_{3\,(max)}$ with Day: Desired RH = 30 – 35 percent, Lights Off

Cage Group	Day	RH actual (percent)	NH_3 (g/ hr/ 100g BW)	$NH_{3\,(max)}$ (g/ hr/ 100g BW)
1 - 4 Test 1	1	71.3	4.69E-04	5.87E-04
	2	66.1	5.44E-04	7.32E-04
	3	70.4	8.30E-04	9.96E-04
	4	62.9	1.26E-03	1.52E-03
	5	61.4	0.00E+00	2.07E-04
	6	54.4	1.34E-03	1.38E-03
	7	52.6	1.96E-03	2.22E-03
	8	58.4	1.86E-03	2.06E-03
	9	61.4	4.31E-03	4.55E-03
	10	57.1	5.62E-03	6.28E-03
9 – 12 Test 1	1	68.0	5.67E-04	6.38E-04
	2	67.7	5.24E-04	7.59E-04
	3	62.8	6.99E-04	8.39E-04
	4	66.2	1.23E-03	1.44E-03
	5	56.8	1.29E-03	1.42E-03
	6	55.5	1.59E-03	1.65E-03
	7	62.4	2.59E-03	2.69E-03
	8	54.1	2.04E-03	2.24E-03
	9	60.2	4.71E-03	4.78E-03
	10	60.5	3.43E-03	4.01E-03
1 – 4 Test 2	1	69.7	9.21E-05	1.11E-04
	2	59.6	0.00E+00	0.00E+00
	3	62.6	5.30E-05	1.06E-04
	4	63.7	2.89E-04	3.06E-04
	5	64.4	5.94E-04	6.29E-04
	6	58.0	1.05E-03	1.10E-03
	7	64.0	1.02E-03	1.41E-03
	8	50.3	-	-
	9	50.6	3.68E-03	4.66E-03
	10	52.4	2.75E-03	3.82E-03

Table 4.1.07 Tabular Variation of RH, NH_3 and $NH_{3\,(max)}$ with Day: Desired RH = 75 – 80 percent, Lights Off

Cage Group	Day	RH actual (percent)	NH_3 (g/ hr/ 100g BW)	$NH_{3\,(max)}$ (g/ hr/ 100g BW)
5-8 Test 1	1	69.7	3.88E-04	4.76E-04
	2	84.8	5.23E-04	6.49E-04
	3	83.8	1.46E-03	1.91E-03
	4	78.2	3.73E-03	4.11E-03
	5	77.7	4.06E-03	4.68E-03
	6	79.6	4.27E-03	4.48E-03
	7	76.3	5.22E-03	5.39E-03
	8	81.1	7.30E-03	7.65E-03
	9	83.4	6.60E-03	6.70E-03
	10	80.6	5.02E-03	5.22E-03
5-8 Test 2	1	73.9	1.28E-04	1.64E-04
	2	83.5	3.69E-05	5.53E-05
	3	79.5	9.19E-05	1.10E-04
	4	83.8	3.71E-04	4.24E-04
	5	86.9	2.15E-03	2.22E-03
	6	75.7	6.75E-03	7.19E-03
	7	87.5	8.16E-03	8.91E-03
	8	77.3	1.00E-02	1.04E-02
	9	75.2	1.39E-02	1.45E-02
	10	77.7	1.16E-02	1.21E-02
9 - 12 Test 2	1	74.3	1.26E-04	1.61E-04
	2	80.4	3.53E-05	5.29E-05
	3	84.4	7.00E-05	1.05E-04
	4	79.4	5.29E-04	6.35E-04
	5	82.8	3.35E-03	3.54E-03
	6	81.1	6.38E-03	6.74E-03
	7	76.5	8.99E-03	9.36E-03
	8	76.8	1.14E-02	1.19E-02
	9	77.6	1.18E-02	1.23E-02
	10	81.0	1.03E-02	1.14E-02

Table 4.1.08 Tabular Variation of H_2O and CO_2 with Day: Test 1, Lights Off

Cage Group	Day	RH actual (percent)	CO_2 (g/ hr/ 100g BW)	H_2O (g/ hr/ 100g BW)
1-4 (Desired RH = 30 - 35 percent)	1	71.3	1.06E+00	1.22E+00
	2	66.1	8.02E-01	1.08E+00
	3	70.4	8.20E-01	9.46E-01
	4	62.9	1.01E+00	8.24E-01
	5	61.4	8.54E-01	7.85E-01
	6	54.4	7.52E-01	8.54E-01
	7	52.6	1.00E+00	8.08E-01
	8	58.4	1.03E+00	7.09E-01
	9	61.4	6.06E-01	6.97E-01
	10	57.1	7.61E-01	7.30E-01
5-8 (Desired RH = 75 - 80 percent)	1	69.7	8.48E-01	**-6.01E-01**
	2	84.8	8.82E-01	1.14E+00
	3	83.8	8.98E-01	7.92E-01
	4	78.2	7.86E-01	8.20E-01
	5	77.7	1.04E+00	5.31E-01
	6	79.6	1.05E+00	9.08E-01
	7	76.3	7.85E-01	5.75E-01
	8	81.1	9.89E-01	7.75E-01
	9	83.4	8.85E-01	8.20E-01
	10	80.6	6.76E-01	1.09E+00
9-12 (Desired RH = 30 - 35 percent)	1	68.0	1.22E+00	1.48E+00
	2	67.7	7.95E-01	1.09E+00
	3	62.8	9.99E-01	8.89E-01
	4	66.2	7.69E-01	8.49E-01
	5	56.8	6.95E-01	1.17E+00
	6	55.5	8.86E-01	8.58E-01
	7	62.4	9.44E-01	8.26E-01
	8	54.1	7.12E-01	7.40E-01
	9	60.2	7.98E-01	5.83E-01
	10	60.5	7.97E-01	7.44E-01

Table 4.1.09 Tabular Variation of H_2O and CO_2 with Day: Test 2, Lights Off

Cage Group	Day	RH actual (percent)	CO_2 (g/ hr/ 100g BW)	H_2O (g/ hr/ 100g BW)
1-4 (Desired RH = 30 - 35 percent)	1	69.7	9.86E-01	1.028E+00
	2	59.6	9.92E-01	1.097E+00
	3	62.6	9.76E-01	8.731E-01
	4	63.7	9.71E-01	8.599E-01
	5	64.4	7.90E-01	7.927E-01
	6	58.0	8.04E-01	8.988E-01
	7	64.0	1.02E+00	6.476E-01
	8	50.3	8.80E-01	7.398E-01
	9	50.6	7.58E-01	9.488E-01
	10	52.4	7.65E-01	5.782E-01
5-8 (Desired RH = 75 - 80 percent)	1	73.9	9.20E-01	8.224E-01
	2	83.5	1.06E+00	4.180E-01
	3	79.5	1.00E+00	7.288E-01
	4	83.8	9.13E-01	1.053E+00
	5	86.9	9.22E-01	7.567E-01
	6	75.7	8.63E-01	6.017E-01
	7	87.5	1.08E+00	7.605E-01
	8	77.3	9.76E-01	8.639E-01
	9	75.2	8.45E-01	7.348E-01
	10	77.7	7.94E-01	6.119E-01
9-12 (Desired RH = 75 - 80 percent)	1	74.3	9.79E-01	7.818E-01
	2	80.4	9.30E-01	7.737E-01
	3	84.4	1.11E+00	9.299E-01
	4	79.4	1.06E+00	9.155E-01
	5	82.8	8.48E-01	8.041E-01
	6	81.1	9.37E-01	7.828E-01
	7	76.5	1.09E+00	8.219E-01
	8	76.8	9.53E-01	8.713E-01
	9	77.6	9.80E-01	1.096E+00
	10	81.0	9.59E-01	1.523E-01

Table 4.1.10 Tabular Variation of H_2O and CO_2 with Day: Desired RH = 30 – 35 percent, Lights Off

Cage Group	Day	RH actual (percent)	CO_2 (g/ hr/ 100g BW)	H_2O (g/ hr/ 100g BW)
1 - 4 Test 1	1	71.3	1.06E+00	1.22E+00
	2	66.1	8.02E-01	1.08E+00
	3	70.4	8.20E-01	9.46E-01
	4	62.9	1.01E+00	8.24E-01
	5	61.4	8.54E-01	7.85E-01
	6	54.4	7.52E-01	8.54E-01
	7	52.6	1.00E+00	8.08E-01
	8	58.4	1.03E+00	7.09E-01
	9	61.4	6.06E-01	6.97E-01
	10	57.1	7.61E-01	7.30E-01
9 – 12 Test 1	1	68.0	1.22E+00	1.48E+00
	2	67.7	7.95E-01	1.09E+00
	3	62.8	9.99E-01	8.89E-01
	4	66.2	7.69E-01	8.49E-01
	5	56.8	6.95E-01	1.17E+00
	6	55.5	8.86E-01	8.58E-01
	7	62.4	9.44E-01	8.26E-01
	8	54.1	7.12E-01	7.40E-01
	9	60.2	7.98E-01	5.83E-01
	10	60.5	7.97E-01	7.44E-01
1 – 4 Test 2	1	69.7	9.86E-01	1.03E+00
	2	59.6	9.92E-01	1.10E+00
	3	62.6	9.76E-01	8.73E-01
	4	63.7	9.71E-01	8.60E-01
	5	64.4	7.90E-01	7.93E-01
	6	58.0	8.04E-01	8.99E-01
	7	64.0	1.02E+00	6.48E-01
	8	50.3	8.80E-01	7.40E-01
	9	50.6	7.58E-01	9.49E-01
	10	52.4	7.65E-01	5.78E-01

Table 4.1.11 Tabular Variation of H_2O and CO_2 with Day: Desired RH = 75 – 80 percent, Lights Off

Cage Group	Day	RH actual (percent)	CO_2 (g/ hr/ 100g BW)	H_2O (g/ hr/ 100g BW)
5-8 Test 1	1	69.7	8.48E-01	**-6.01E-01**
	2	84.8	8.82E-01	1.14E+00
	3	83.8	8.98E-01	7.92E-01
	4	78.2	7.86E-01	8.20E-01
	5	77.7	1.04E+00	5.31E-01
	6	79.6	1.05E+00	9.08E-01
	7	76.3	7.85E-01	5.75E-01
	8	81.1	9.89E-01	7.75E-01
	9	83.4	8.85E-01	8.20E-01
	10	80.6	6.76E-01	1.09E+00
5-8 Test 2	1	73.9	9.20E-01	8.22E-01
	2	83.5	1.06E+00	4.18E-01
	3	79.5	1.00E+00	7.29E-01
	4	83.8	9.13E-01	1.05E+00
	5	86.9	9.22E-01	7.57E-01
	6	75.7	8.63E-01	6.02E-01
	7	87.5	1.08E+00	7.61E-01
	8	77.3	9.76E-01	8.64E-01
	9	75.2	8.45E-01	7.35E-01
	10	77.7	7.94E-01	6.12E-01
9 - 12 Test 2	1	74.3	9.79E-01	7.82E-01
	2	80.4	9.30E-01	7.74E-01
	3	84.4	1.11E+00	9.30E-01
	4	79.4	1.06E+00	9.16E-01
	5	82.8	8.48E-01	8.04E-01
	6	81.1	9.37E-01	7.83E-01
	7	76.5	1.09E+00	8.22E-01
	8	76.8	9.53E-01	8.71E-01
	9	77.6	9.80E-01	1.10E+00
	10	81.0	9.59E-01	1.52E-01

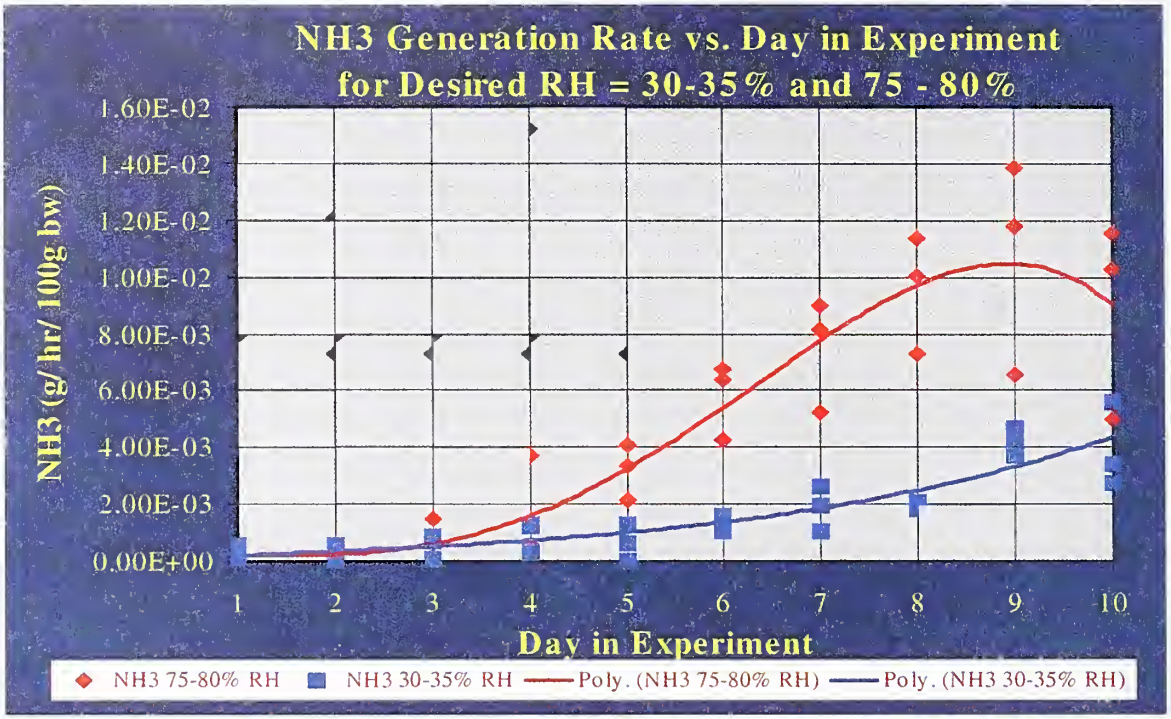


Figure 4.36 *Variation of NH3 Generation Rate with Day in Experiment*

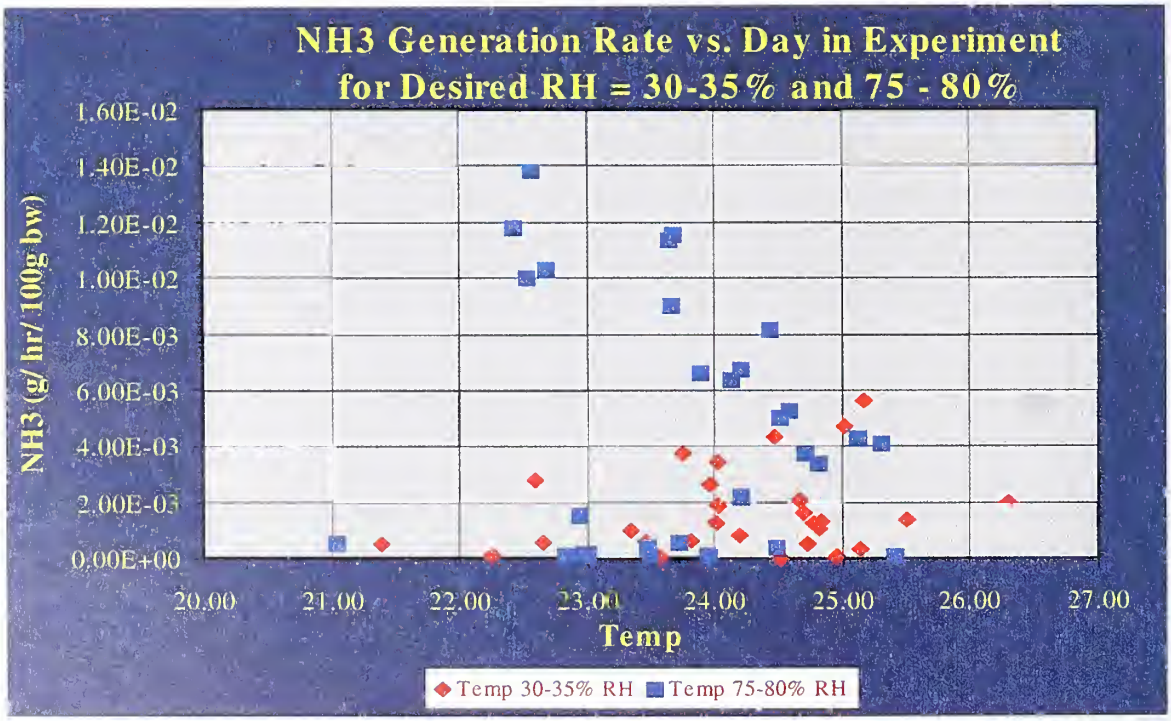


Figure 4.37 *Variation of NH3 Generation Rate with Cage Temperature*

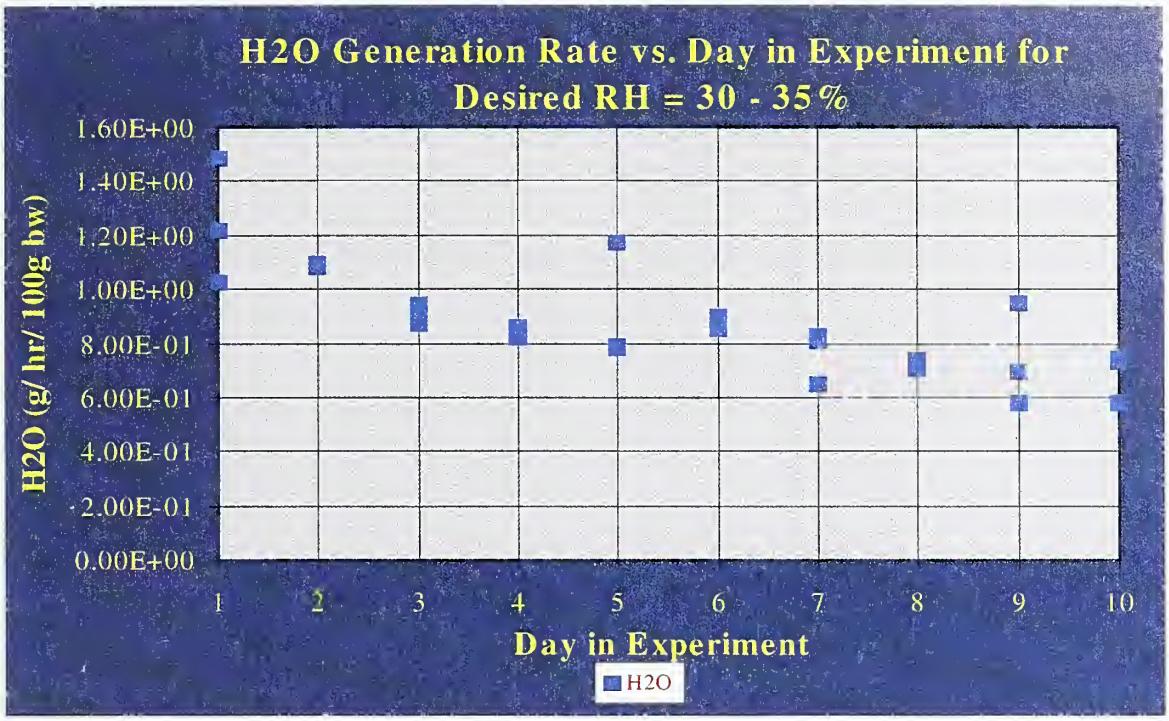


Figure 4.38 *Variation of H_2O Generation Rate with Day in Experiment: Desired RH = 30 – 35 percent.*

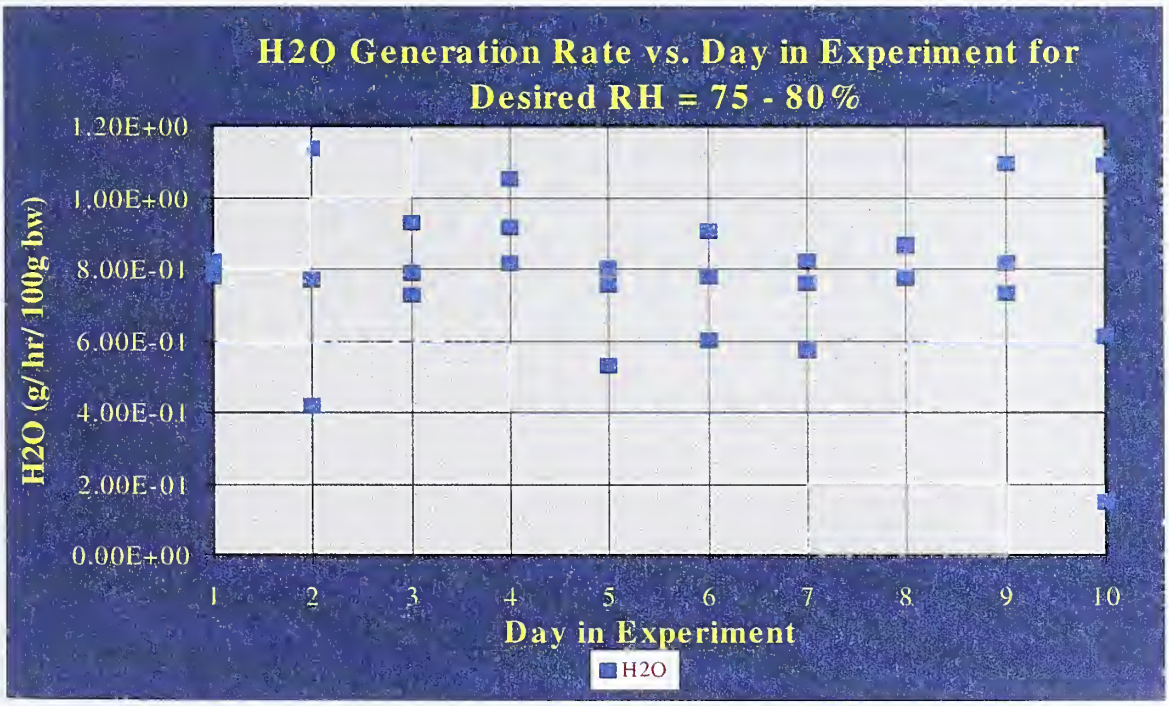


Figure 4.39 *Variation of H_2O Generation Rate with Day in Experiment: Desired RH = 75-80 percent.*

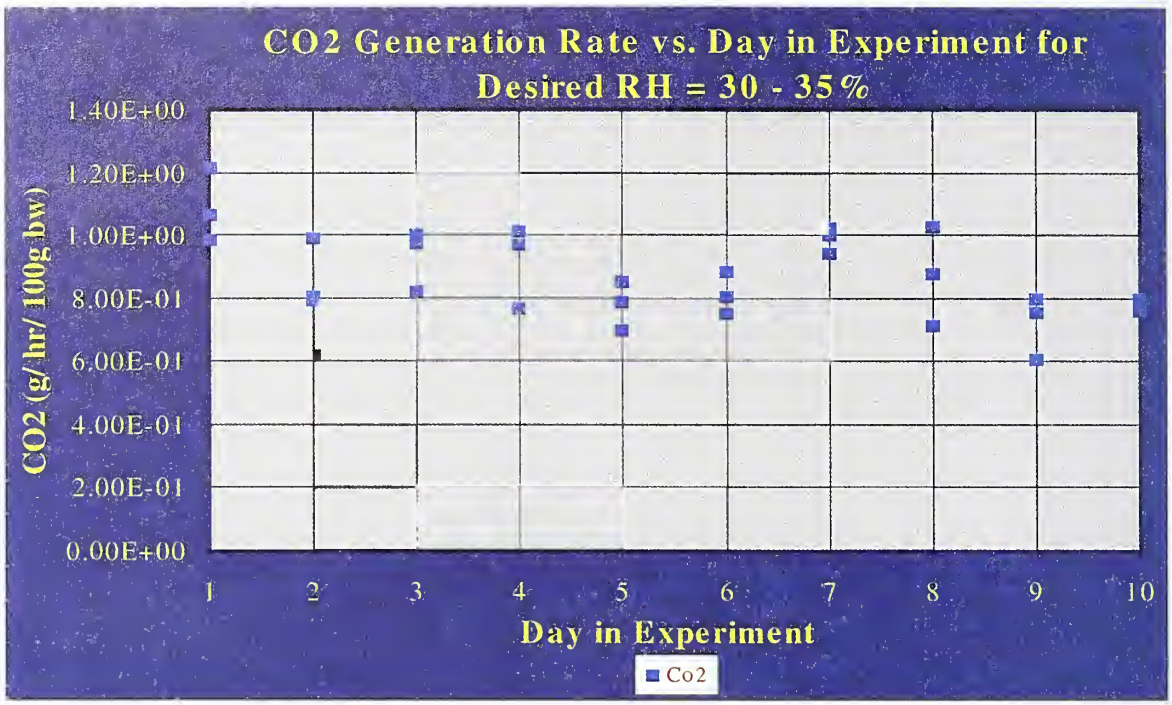


Figure 4.40 *Variation of CO_2 Generation Rate with Day in Experiment: Desired RH = 30 –35 percent.*

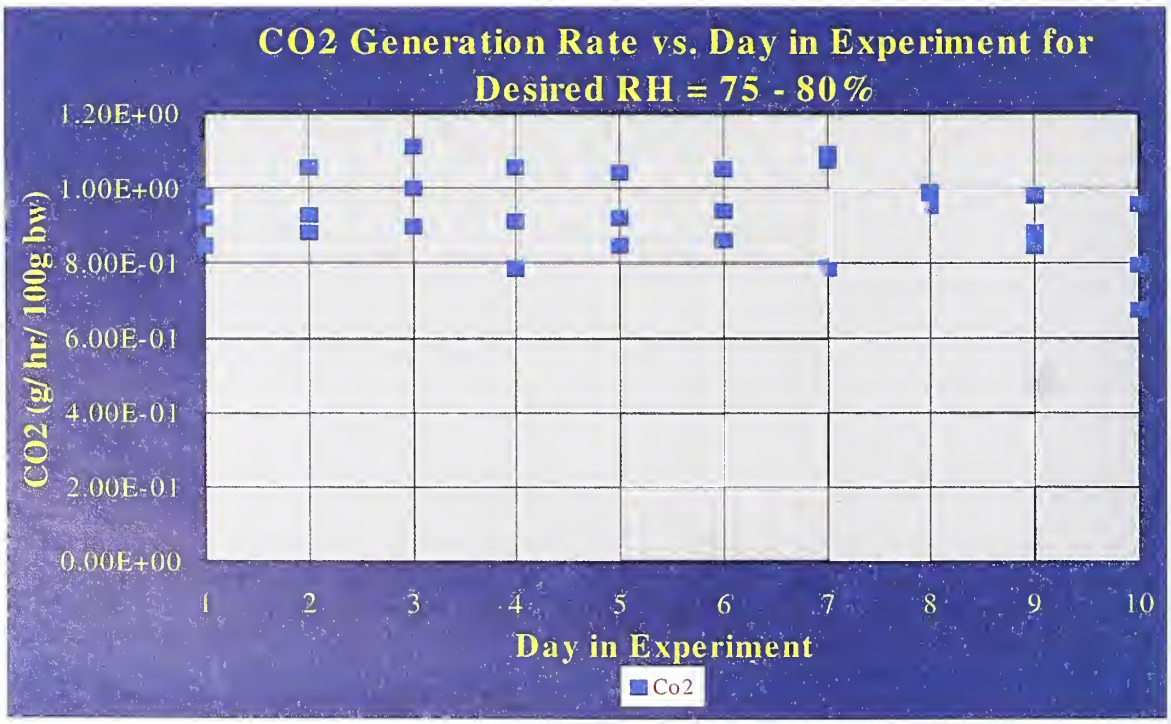


Figure 4.41 *Variation of CO_2 Generation Rate with Day in Experiment: Desired RH = 75 – 80 percent.*

4.1.2.8.3 Consideration of Heat Generation

Using the O_2 consumption data averages from the two tests for the different desired RH values, and the lights on/off conditions, the heat generation from the mice can be calculated. The results are shown in table 4.1.12 below, and are presented graphically in figure 4.42:

Table 4.1.12. Heat Generation Rates for Lights On/ Off Conditions in Tests 1 and 2.

	O_2 Consumed (L/hr/ kg bw)	**Heat Production (Kcal/hr/Kg BW)***	**Heat Production per cage (W/ 100g bw)**
Test 1:			
Desired RH 30–35 (Lights On)	3.49	16.83	1.96
Desired RH 30–35 (Lights Off)	4.16	20.06	2.33
Desired RH 75-80 (Lights On)	3.95	19.83	2.30
Desired RH 75-80 (Lights Off)	4.14	19.98	2.32
Test 2:			
Desired RH 30-35 (Lights On)	4.06	19.57	2.27
Desired RH 30-35 (Lights Off)	4.91	23.71	2.76
Desired RH 75-80 (Lights On)	5.46	26.34	3.06
Desired RH 75-80 (Lights Off)	6.00	28.94	3.36

* Heat production was based on a heat production rate of 4.825Kcal/L O_2.

It can be noted that there is an increase in heat generation between the lights on and lights off conditions, and there is also an increase on moving from a low RH to a high RH cage condition. The average value from all the experiments is 2.55 W/100g bw, an 11 percent difference from the ASHRAE value of 2.3 W/ 100g bw, obtained from equation 4.1 (see section 4.1.1.2). This indicates that the current experiment is consistent with previous recommendations.

4.1.2.8.4 Summary of Experimental Data

The average mass generation rates of CO_2 and H_20, the average consumption rates of O_2, and the generation rates of heat for the scotophase and photophase from all experimental tests are tabulated below in Table 4.1.13, and presented graphically in figure 4.43. The table and figure emphasize that the generation rates are higher during the scotophase than the photophase.

Table 4.1.13 Average Gas Mass Generation/ Consumption Rates, and Average Generation Rates of Heat for the Scotophase and Photophase from all Experimental Tests.

Variable	Scotophase	Photophase
CO_2 (g/ hr/ 100g bw)	9.05e-1	6.92e-1
CO_2 (ppm)	6147	4554
H_20 (g/ hr/ 100g bw)*	8.31e-1	
O_2 (g/ hr/ 100g bw)	6.60e-1	6.75e-1
Heat (W/ 100g bw)	2.69	2.40

* No distinction was made between lights on/ off in calculation of water generation.

The NH3 data cannot be summarized in such a way, because the generation rate varies significantly with RH, light phase and the day in the experiment. figure 4.44 shows the variation of NH3 (ppm) with the day in experiment for different RH levels, and for scotophase and photophase.

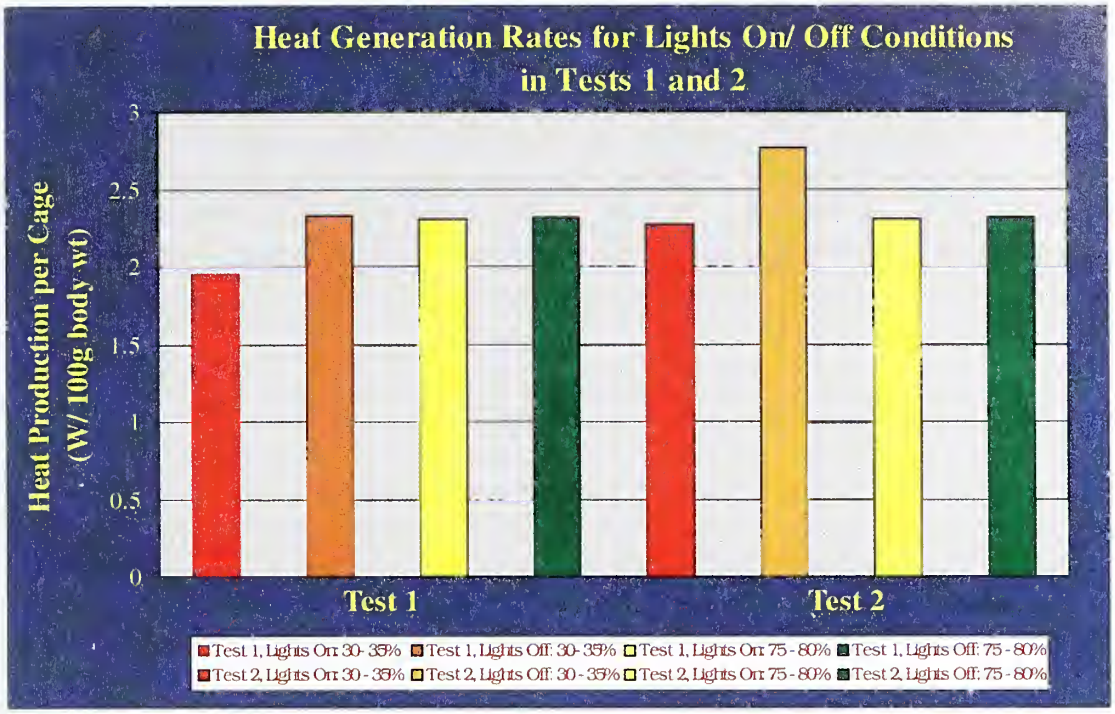


Figure 4.42 *Heat Generation Rates for Lights On/ Off Conditions in Tests 1 and 2.*

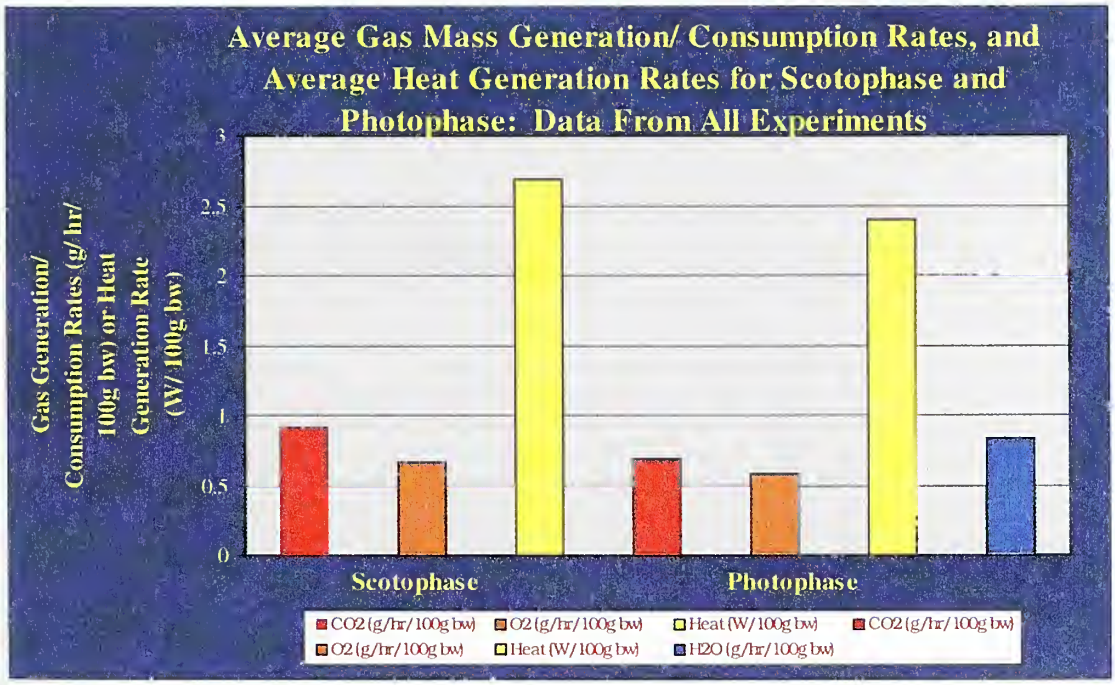


Figure 4.43 *Average Gas Mass Generation/ Consumption Rates, and Average Heat Generation Rates for Scotophase and Photophase: Data From All Experiments.*

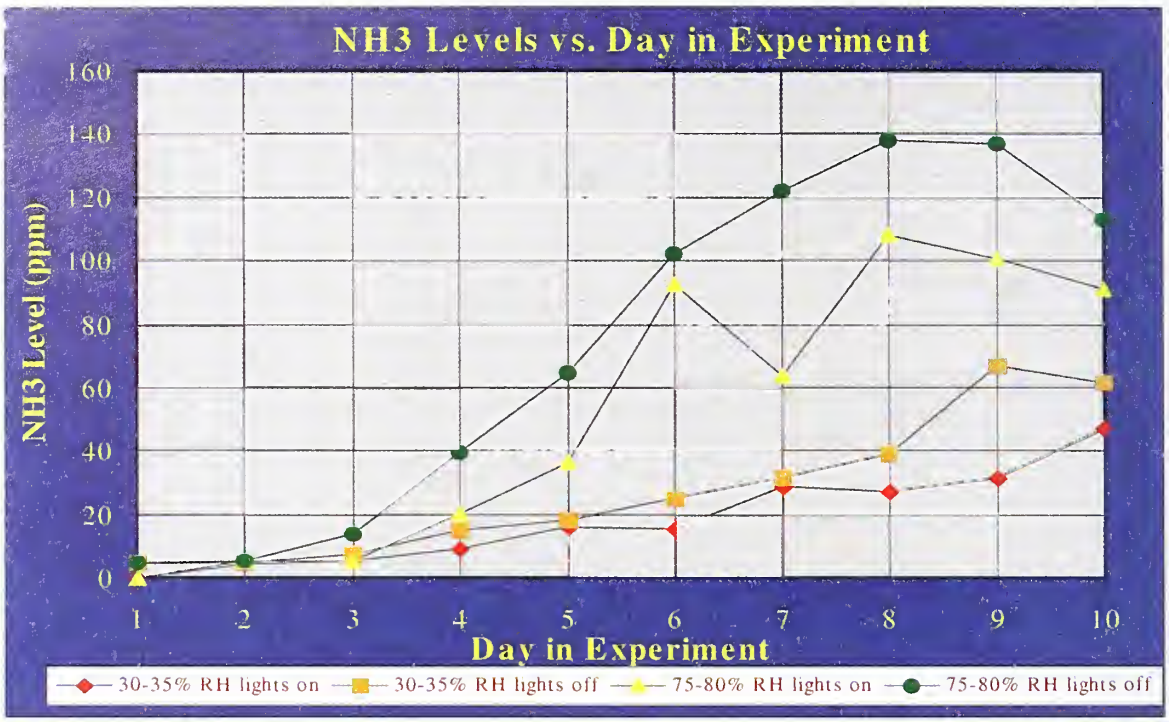


Figure 4.44 *Variation of NH3 Level (ppm) with Day in Experiment*

4.1.3 Room Condition

4.1.3.1 Experimental Cases

4.1.3.1.1 Empty Room: Description of Apparatus

The empty testing room, that measured 3.66m x 2.44m x 2.44m high (12' x 8' x 8'), was located within the larger air-conditioned UIUC room ventilation simulator (RVS). The room is shown in figure 4.45). The RVS is described in Wu et al., (1990). The placement of the room in the RVS allowed the supply air to the testing room to be precisely controlled. The RVS is capable of maintaining air temperature at any point between –25.0 to 40.0 °C (-13.0 to 104.0 °F) with an accuracy of ±1.5 °C (±2.7 °F), year around. In this study, room temperature in the RVS was maintained at 22.0±1.5 °C (71.6±2.7 °F). In this case, air was supplied by a TAD diffuser (Krueger 2-way total air diffuser), that was centered on the ceiling of the room. The diffuser, that measured 0.61m (24") long (east-west wise) and 0.57m (22.5") wide (north-south wise) was oriented to direct air towards the long axis of the room. The discharge surface of the diffuser was curved and the lowest point was 0.14m (5.5") below the ceiling. The room air exhaust was a 0.30m x 0.30m (12" x 12") aluminum grille with a 20 percent open area and was located in one corner of the ceiling. The exhaust outlet was 0.2m (8") away from both the west and north walls. The only other item of geometry in the room was the door, that measured 0.91m x 2.13m (3' x 7'), and was located centrally on the north wall. The door had a 6.4e-3m (¼") crack on its bottom, that allowed pressurization of the room.

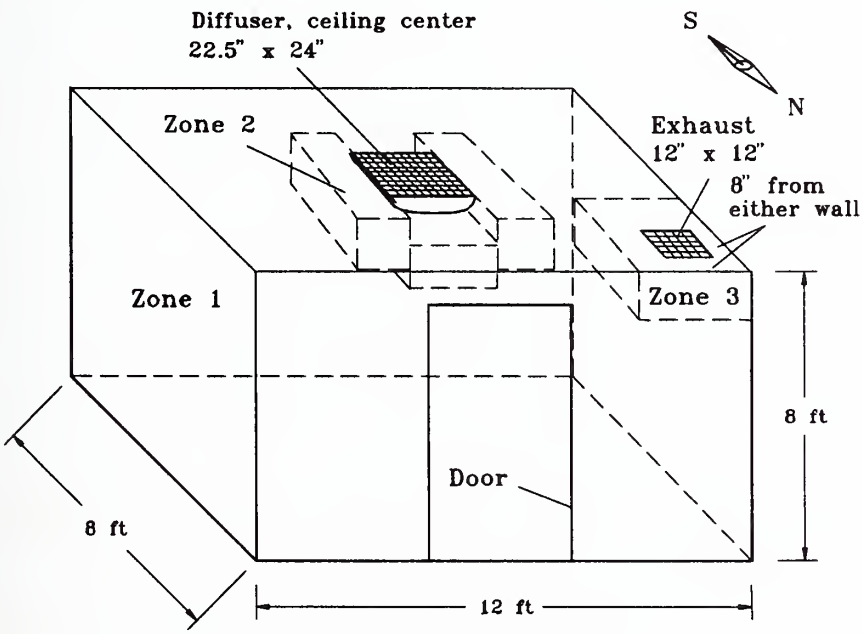


Figure 4.45 *Layout of the testing room and the zones used for data collection. Dashed lines show the borders of zones used in data collection.*

4.1.3.1.2 Empty Room: Test Procedure

The room air temperature was operated at 22.0 °C (71.6 °F) with a plus or minus tolerance of 1.5 °C (2.7 °F) throughout the room. Difference between the supply air temperature and the mean of the room surface temperatures was less than 1.5 °C (2.7 °F). The room surfaces were insulated and both the interior and exterior of the room were maintained at the same temperature. All surface temperatures were measured with an infrared thermographer (Cole-Parmer Instrument Co. model 39650-12). Surface temperatures were recorded at the beginning and end of each batch of data (approximately four hours). Measurements were taken at the center of each wall and the floor, and on the four sides of the ceiling halfway between the diffuser and the walls. These temperature measurements are tabulated in appendix I: section 4.3.1.

The room was operated at a slight positive pressure (at 10pa (0.04" of H_2O column) to eliminate incoming air currents other than the diffuser. The supply airflow rate was controlled at a constant value of 128 cfm (6.0e-2 m^3/s), that was 10 air changes per hour (ACH) for the testing room. The exhaust airflow rate was maintained at 102±2 cfm (appendix I: section 4.3.1).

Air volume flow rates into the room diffuser and out of the exhaust grill were measured with precision nozzles machined according to specifications given in the ANSI/ASHRAE Standard 51-1985. The nozzles were located in the ducts outside of the room. Airflows were controlled and measured continuously during each experimental run by measuring the pressure drop across the nozzles with a manometer. Duct fans were placed downstream of each nozzle. The supply fan was adjusted to provide the required airflow into the room and the exhaust fan was adjusted to provide the required static pressure in the room.

Three zones were used for data collection. The entire room airspace was zone 1. The air space 0.30m (1') from the diffuser surface was zone 2. The air space 0.30m (1') from the exhaust outlet was zone 3 (figure 4.45). The total number of measurement locations is shown in table 4.1.13. Temperature, air velocity, and turbulence intensity were measured every 5.1e-2m (2") within 0.30m (12") of the diffuser and exhaust, and every 0.15m (6") throughout the rest of the room. Temperature was measured with type-T thermocouples. The temperature sensors were calibrated in a temperature controlled water bath that was set according to a SAMA thermometer. The air velocity and turbulence intensity levels were measured with sensors that were designed and constructed at the Bioenvironmental Engineering Research Laboratory (BERL) at the UIUC. This air velocity sensor has a thermistor sensing head that is maintained at a constant temperature and is described in Li (1994). The accuracy is plus or minus 3 percent of reading or plus or minus 2 fpm, whichever is greater. The air velocity sensors were calibrated prior to the experiment in a TSI Certified Air Velocity Calibrator (model 8390). The air velocity sensor is omni-directional and has a fast response time so it can measure turbulence intensity as well as air velocity. Outputs from the temperature and air velocity sensors were collected on a data acquisition system (DAS-8 with EXP-16 expansion boards, Keithley-Metrabyte, Inc.) and an IBM compatible computer.

To determine turbulence intensity, air velocities were measured at a sampling rate of 40 Hz. Justifications of this sampling frequency are in appendix I: section 4.1. Preliminary data were collected at different sampling frequencies to verify the validity of using 40 Hz for this overall study. Air velocity data were collected for 6 seconds to obtain 240 data samples at each point.

Table 4.1.13 Number of Collection Points and Data Numbers for Empty Room Measurements

Zone	Number of Collection Points	Number of Variable Data Collected[a]	Number of Air Velocity Data Collected[b]
Zone 1	5625	33750	6.75e+6
Zone 2	3240	19440	3.888e+6
Zone 3	1920	11520	2.304e+6

a - number of collection points * number of variables (6)
b - number of collection points * number of air velocity variables * 240 (40Hz sampling over 6 seconds)

Sensors were mounted on a traverse system (positioned to minimize airflow interference) that moved the sensors throughout the room, see figures 4.46 and 4.47. The traverse was computer controlled to ensure the accuracy of locations of each measurement point. No people were in the test room during or 10 minutes prior to any measurements to ensure the room air was not disturbed and in a steady state. All heat generating devices (e.g., traverse power supply, amplifiers) were kept out of the room except for the sensing system. Measurements were not taken until after the door was closed for 10 minutes and room airflow reached steady-state conditions. The room air velocity field and temperature achieved steady-state 4 minutes after the door was closed.

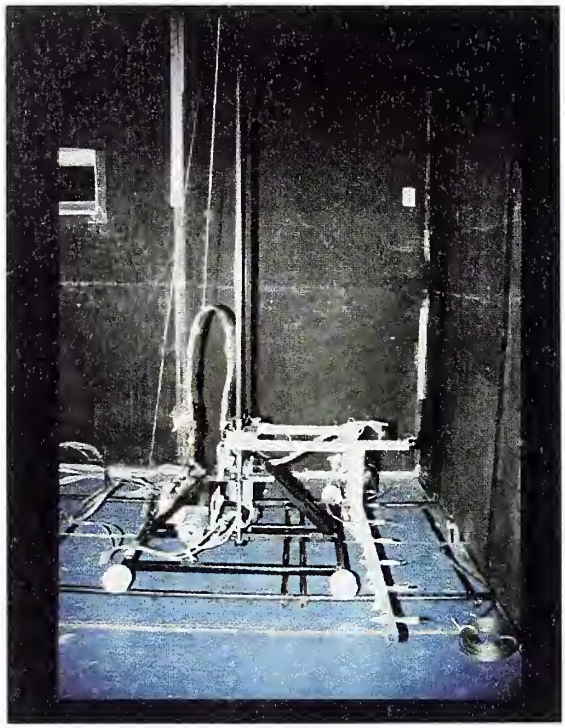


Figure 4.46 *Automatic traverse system.*

Figure 4.47 *Empty Room Measurement Taking.*

4.1.3.1.3 Room With Racks, Cages and Simulated Animals: Apparatus Description

The same room used in the empty room analysis with the same supply and exhaust flow rates and diffuser and exhaust were outfitted with three racks, rodent cages, and a sink (figure 4.48). Each rack was 0.61m D x 1.52m H x 1.83m W (24" x 60" x 72") with 6 solid shelves (figure 4.49). The shelf at the top of the rack was 1.52m (60") from the floor. The distances between two shelves (center to center) was 0.28m (11"), while the shelves themselves were 1.25e-2m (½") thick. All racks were filled to capacity with mouse cages (7 cages per shelf; 42 cages per rack) and the cages were shoebox type with were 1.25e-2m (½") of hardwood shavings bedding. The sink cabinet size was 0.61m W x 0.61m D x 0.81m H (24" x 24" x 32"). A 200 ohm precision resistance heater was placed in each cage to generate 2.42 W to simulate the heat load of the mice. CO_2 was supplied through diffuser stones at 3.75e-2m (9.5") above the bedding level towards the front of each cage near the heaters. The total CO_2 rate supplied to the room was 990 mL/min. Water bottles and simulated feed obstruction were included in each cage.

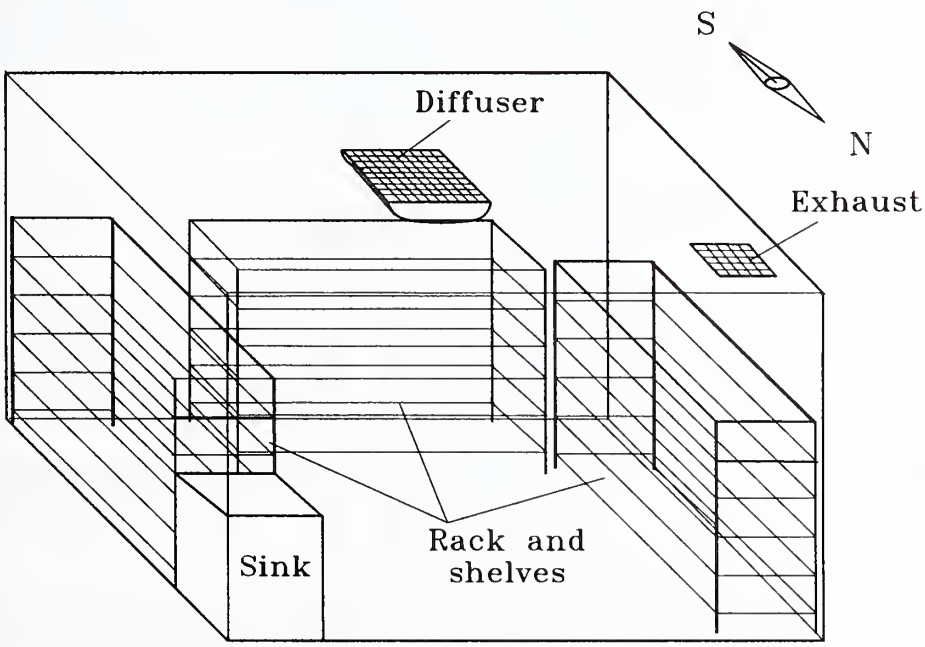


Figure 4.48 *Layout of the testing room with racks and sink. Each rack had six shelves and each shelf had seven cages.*

4.1.3.1.4 Room With Racks, Cages and Simulated Animals: Test Procedure

The test room was divided into seven zones for data collection, as indicated in figure 4.50. The total number of measurement locations is shown in table 4.1.14. The room mean air velocity, median air velocity, range of air velocity, temperature, TI, and CO_2 concentration patterns were determined at 0.30m (12") increments throughout the room. Measurements started 0.05m (2") from racks and walls. Temperature measurements were obtained with type -T thermocouples, air velocity with the BERL air velocity sensors, and CO_2 with the Fuji gas monitor (Fuji Electric Co., model ZEP5YA31). This equipment and their calibration procedures were described section 4.3.1.2. All sensors were calibrated prior to the start of this experimental sequence except for the thermocouples. The sensors were moved around the room with a traverse system as described earlier so no people entered the room during or 10 minutes prior to any measurements. A view of the measurement sensors on the traverse system is shown in figure 4.51.

Figure 4.49 Animal Room Macroenvironmental Measurements: Cage Rack.

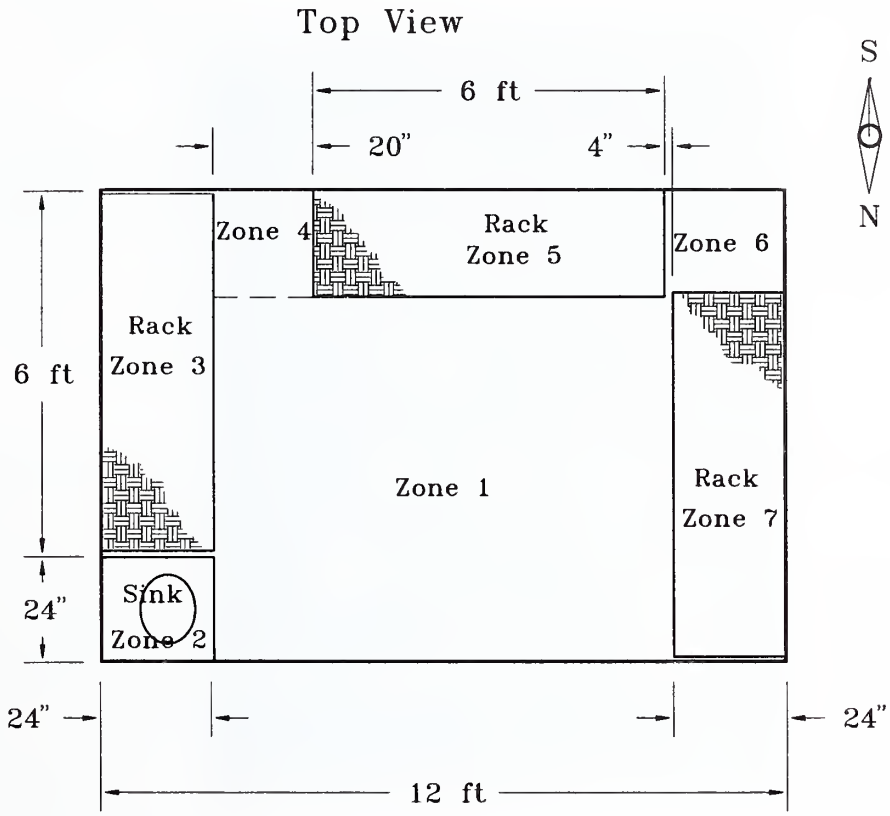


Figure 4.50 *Top view of zones in the room: Three racks are identical, each rack has six shelves and each shelf supports seven mouse cages.*

Table 4.1.14 Number of Collection Points and Data Numbers for Populated Room Measurements

Zone	Number of Collection Points	Number of Variable Data Collected[a]	Number of Air Velocity Data Collected[b]
Zone 1	441	3087	5.292e5
Zone 3	28	196	3.36e4
Zone 5	52	364	6.24e4
Zone 7	28	196	3.36e4

a - number of collection points * number of variables (7)
b - number of collection points * number of air velocity variables * 240 (40Hz sampling over 6 seconds)

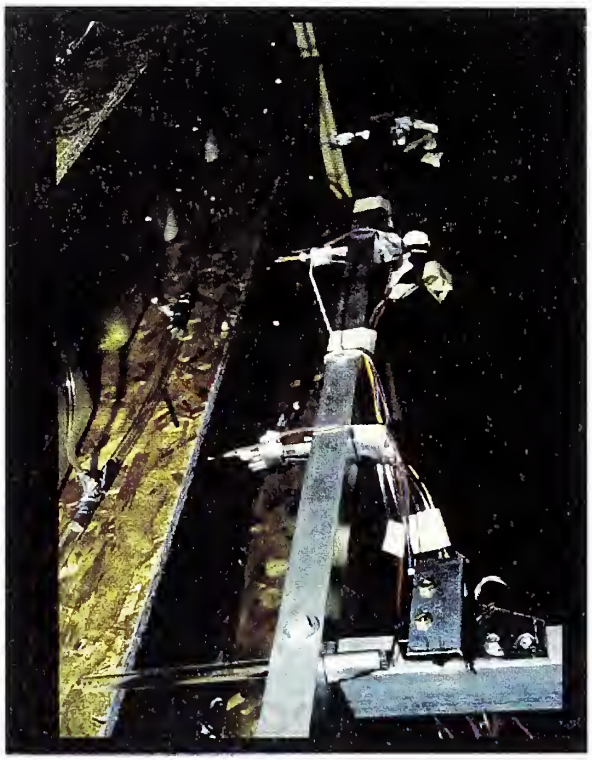


Figure 4.51 *Animal Room Macroenvironmental Measurement Sensors.*

4.2 CFD Simulations and Validation against Experimental Data

4.2.1 Cage Condition

A series of CFD models was constructed to simulate the cage wind tunnel experiments. The accurate modeling of the cage is an important stage in the project. In particular, the CFD cage model, as validated against the experimental data obtained in the wind tunnel, is used in the CFD animal research facility models as part of the racks. The two sets of boundary conditions that are of most concern are those associated with the transfer mechanisms into and out of the cage, namely the side cracks and the top of the cage, that includes the filter.

4.2.1.1 Description of CFD models

All the models contained the same basic components and modeling philosophy: changes between the models reflected the different experimental procedures.

The walls of the tunnel were specified to define the shape of the experimental wind tunnel. Typical CFD models for the tunnels are shown in figures 4.52 to 4.54. The ventilation system specification for the tunnel was the definition of a 0.4 m x 0.5 m (15.75" x 20") opening at the entrance of the tunnel, and an extract at the opposite end. The size of the extract, 0.14m x 0.14m (5.3" x 5.3"), was defined such that the cross-sectional area was the same as in the physical situation. The mass flow rate set through the exhaust was varied to produce the same air velocities through the tunnel section as in the experiments, with the value dependent on the desired speed. The three screens and two filters in the tunnel were modeled using 0.4 m x 0.5 m (15.75" x 20") planar resistances. The loss coefficients for each were set according to the free area ratio of the object. The values are listed below in Table 4.2.01, and are based on Idelchik (1989):

Table 4.2.01. Free Area Ratios and Loss Coefficients Used for Tunnel Straightening Media

Device	Free Area Ratio	Loss Coefficient
Screen 1	0.6	2.00
Screen 2	0.4	8.25
Screen 3	0.33	14.35
Filters 1,2	0.5	4.00

The shelf on that the cage sits was defined as a rectangular block of dimension 2.5e-2m x 0.30 m x 0.50 m (1" x 11.8" x 20"). The shelf was located 0.10m (4") from the floor of the tunnel for the parallel and perpendicular orientation experimental measurements, with the center of the shelf located at the center of the tunnel section. In the vertical orientation experiments, the shelf was located centrally within the tunnel.

Placed on the shelf was the CFD model representation of the cage. A typical representation of the cage, without instrumentation, is shown in figure 4.55. The dimensions of the cage were set as 0.27 m x 0.16m x 0.21m (10.7" x 6.38" x 8.39"): these dimensions retained the same volume as in the physical case. The sides of the cage were modeled as thin plates, with the thickness and conductivity of the plates set to those of the cage polycarbonate. The bottle was represented using a combination of rectangular prisms and cuboid blocks. The volume of the bottle was retained, as was the location of the bottle in the cage. A food supply was modeled using two triangular prisms. The bedding was represented as a dimension 0.27m x 0.16m x 1.3e-2m (10.7" x 6.38" x 0.5") rectangular block. The alternative representations of the mice heater were modeled using rectangular blocks. In particular, the original heater was modeled as a 1.59e-2m x 0.32e-2m x 0.32e-2m (5/8" x 1/8" x 1/8") block, with the heat flux set to 2.3W, while the huddled mice were modeled as a block of dimension 0.11m x 8.6e-1m x 2.2e-2m (4 1/4" x 3 3/8" x 7/8"), with the surface temperature set to 26.7°C (80.0°F).

There are two transfer mechanisms for the air and tracer gas to enter/ leave the cage, namely the top of the cage, that includes filter media, and the side cracks of the cage.

The top of the cage has two constituent parts that had to be represented using CFD boundary conditions: the filter media; and the top of the cage itself, that consists of regular arrays of holes in the polycarbonate material. The filter material was identified as Reemay #2024, 12 mils, 2.1 oz/ yd^2. Using manufacturer's data, a pressure drop vs. wind tunnel speed graph could be plotted in figure 4.56. The profile was then approximated to a polynomial expression that could be converted to CFD boundary conditions. In particular, the polynomial expression can be expressed as:

$$DP = 70.277\, v^2 + 307.37\, v \qquad (4.22)$$

As the average velocities through the filter are relatively small (of the order of 0.17 cfm (8e-4 m/s)), the linear contribution dominated the pressure drop. Using boundary conditions defined in section 5.1.6.2, the first term of the right hand side was represented using a planar resistance, while the second term was represented using a planar source of momentum. The loss coefficients were set appropriately for each boundary condition to replicate the polynomial expression. As the flow through the filter media is laminar, the turbulent viscosity at the plane of the media was reduced to very low levels. To achieve this, the value of k (the turbulent kinetic energy) was set at 1e-5 at the planar source, while ε (the rate of dissipation of k), was set to 1e5.

The cage top material itself was represented through the calculation of the free area ratio of the top surface, and the addition of the loss coefficient to the planar resistance term. The free area ratio was calculated to be 0.35, that gives a loss coefficient of 12.35 (Idelchik (1989)).

The settings for the side crack boundary conditions were the most problematical to specify because of physical uncertainties. In particular, the top lid of the cage does not fit well on the lower section of the case because the meshing is often deformed. The first step was to define

these cracks as planar resistances of height 6.4e-3m (¼"). Initially using the results of the series set base experiments, the values for the loss coefficients on the side cracks were varied until the predicted CFD values for the cage ACH reasonably matched the experimental data over a range of tunnel velocities for each of the three orientations. These loss coefficient values were then tested against the lower injection rate experimental series (series sets one to four, to eight) to ensure good agreement. Any adjustments to the loss coefficients were then tested over the a range of experimental data sets to ensure that the values were applicable to all possible conditions that the cage could be presented within the animal facility room environment.

4.2.1.2 Results from CFD Simulations

In this section, variable plots from a typical cage will be considered, then the comparison of the CFD results with the experimental data will be presented.

4.2.1.2.1 Plots from Typical Cage CFD Simulation

A single CFD simulation will be considered to indicate the physical features that can be predicted using CFD, which are otherwise difficult to determine using experimental procedures. In particular, the CFD allows the determination of flow patterns within the cage, as well as temperature and concentration distributions.

The close-up plot of the vector field at the plane halfway through the tunnel for the Series Sets Six: Parallel Orientation, Heater On (SMO) 40 fpm (0.2 m/s) case is shown in figure 4.57. Note that the key accompanying the plot indicates speed in m/s (to convert to fpm, multiply by 200). Externally from the cage, the most prominent feature is the recirculation region immediately behind the cage. Internally, the main feature is the buoyant plume resulting from the SMO. However, it is noticeable that, apart from the plume, there are few flow patterns present within the cage of any great magnitude. In particular, although there is obviously strong external flow that is impinging directly onto the side of the cage, relatively small amounts of flow actually enter it.

The equivalent close-up plots of the temperature and CO_2 concentration fields are shown in figures 4.58 and 4.59 respectively. Note that the keys indicate the temperature in °C and concentration in kg of species/ kg of air (to convert to ppm multiply by 1e6*(28.96/44)) respectively. The temperature plot shows the distinct plume resulting from the SMO. This plume dominates the distribution of the concentration also, as the CO_2 is entrained into this flow feature. The concentration plot also indicates the clear stratification of the CO_2 in the cage. That is due to the density difference between the CO_2 and air. This stratification makes the matching of the CFD results to the experimental data difficult, as relatively small spatial changes result in marked differences in the level of concentration.

4.2.1.2.2 Comparison of CFD Results vs. Experimental Data

Presented below, in tables 4.2.02 to 4.2.12, are a series of comparisons between the experimental data sets and equivalent CFD simulation cage ACH for the chosen optimal values for the cage side crack loss coefficients. Note that, because of time constraints, only a representative sample could be considered from the wide range of experimental data available. The focus of the sample was to pick orientations that the cage was more likely to experience in the animal facility room environment, in particular, parallel cage orientation, and appropriate air velocities, in particular, 40 fpm (0.2m/s) and below.

A complete listing of the experimental cage ACH data is given in appendix I: section 2.2.

The comparisons show good agreement between the experimental data and CFD simulation results for the range of experimental series considered. In the majority of cases considered, the difference between the experimental and CFD results is under 20 percent. This error can be considered reasonable for this set of validation and calibration exercises. In particular, the CFD results show that the calculated value for the cage ACH is sensitive to the exact location of the sampling tubes, and the sampling tube holes themselves: this is because of the stratification of the CO_2 or SF_6 concentrations in the cages (see figure 4.59). Relatively small variations from the quoted location of the experimental sampling tubes would translate to errors in the CFD calculation. Further, as table 4.2.02 demonstrates, some level of error should be accepted in the experimental procedure.

Table 4.2.02. Comparison of CFD results against Series Set Base: Parallel Orientation Results.

Tunnel Velocity (FPM)	**Ventilation Rate (CFM)** **1 l/min CO_2** *Parallel - Heater On*		
	CFD	**Series Set Base**	**Series Set Base (Repeat)**
20	0.15	0.19	--
30	0.17	0.21	0.18*

* The percent difference between the two separate experimental readings is 14.3 percent.

Table 4.2.03. Comparison of CFD results against Series Sets Two: Parallel Orientation, SF_6 Results

Tunnel Velocity (FPM)	Ventilation Rate (CFM) 0.1 l/min SF_6 *Parallel - Heater On*	
	CFD	Set Two
20	0.04	0.04
30	0.05	0.05
40	0.06	0.06

Table 4.2.04. Comparison of CFD results against Series Sets Two: Perpendicular Orientation, Heater On, SF_6 Results

Tunnel Velocity (FPM)	Ventilation Rate (CFM) 0.1 l/min SF_6 *Perpendicular - Heater On*	
	CFD	Set Two
20	0.05	0.04
30	0.05	0.05
40	0.06	0.05

Table 4.2.05. Comparison of CFD results against Series Sets One and Three: Parallel Orientation, Heater On Results.

Tunnel Velocity (FPM)	Ventilation Rate (CFM) 0.1 l/min CO_2 Parallel - Heater On		
	CFD	Series Set One	Series Set Three
20	0.07	0.07	0.08
30	0.09	0.10	0.11
40	0.10	0.10	0.13

Table 4.2.06. Comparison of CFD results against Series Sets Three: Parallel Orientation, Heater Off Results.

Tunnel Velocity (FPM)	Ventilation Rate (CFM) 0.1 l/min CO_2 Parallel - Heater Off		
	CFD	Series Set Three	Series Set Three (Repeat)
20	0.10	0.09	--
30	0.10	0.12	0.09*
40	0.12	0.15	--

* The percent difference between the two separate experimental measurements is 25 percent

Table 4.2.07. Comparison of CFD results against Series Sets Three: Perpendicular Orientation, Heater On Results.

Tunnel Velocity (FPM)	Ventilation Rate (CFM) 0.1 l/min CO_2 *Perpendicular - Heater On*	
	CFD	Series Set Three
20	0.15	0.08
30	0.18	0.14
40	0.21	0.24

Table 4.2.08. Comparison of CFD results against Series Sets Three: Perpendicular Orientation, Heater Off Results.

Tunnel Velocity (FPM)	Ventilation Rate (CFM) 0.1 l/min CO_2 *Perpendicular - Heater Off*	
	CFD	Series Set Three
20	0.15	0.06
30	0.18	0.09
40	0.21	0.17

Table 4.2.09. Comparison of CFD results against Series Sets Six: Parallel Orientation, Heater On (DMH) Results

Tunnel Velocity (FPM)	Ventilation Rate (CFM) 0.1 l/min CO_2 *Parallel - Heater On (DMH) Sealed Lip*	
	CFD	Series Set Six
20	0.06	0.07
40	0.06	0.07

Table 4.2.10. Comparison of CFD results against Series Sets Six: Parallel Orientation, Heater On (SMO) Results

Tunnel Velocity (FPM)	Ventilation Rate (CFM) 0.1 l/min CO_2 *Parallel – Heater On (SMO) Sealed Lid*	
	CFD	Series Set Six
20	0.04	0.04
40	0.06	0.04

Table 4.2.11. Comparison of CFD results against Series Sets Six: Perpendicular Orientation, Heater On (SMO) Results

Tunnel Velocity (FPM)	Ventilation Rate (CFM) 0.1 l/min CO_2 *Perpendicular – Heater On (SMO) Sealed Lid*	
	CFD	Series Set Six
20	0.05	0.05
40	0.06	0.05

Table 4.2.12. Comparison of CFD results against Series Eight Results

Cage Orientation	Ventilation Rate (CFM) 0.1 l/min CO_2 *Parallel/ Perpendicular – Heater On (SMO)*	
	CFD	Series Set Eight
Parallel	0.10	0.10
Perpendicular	0.09	0.08

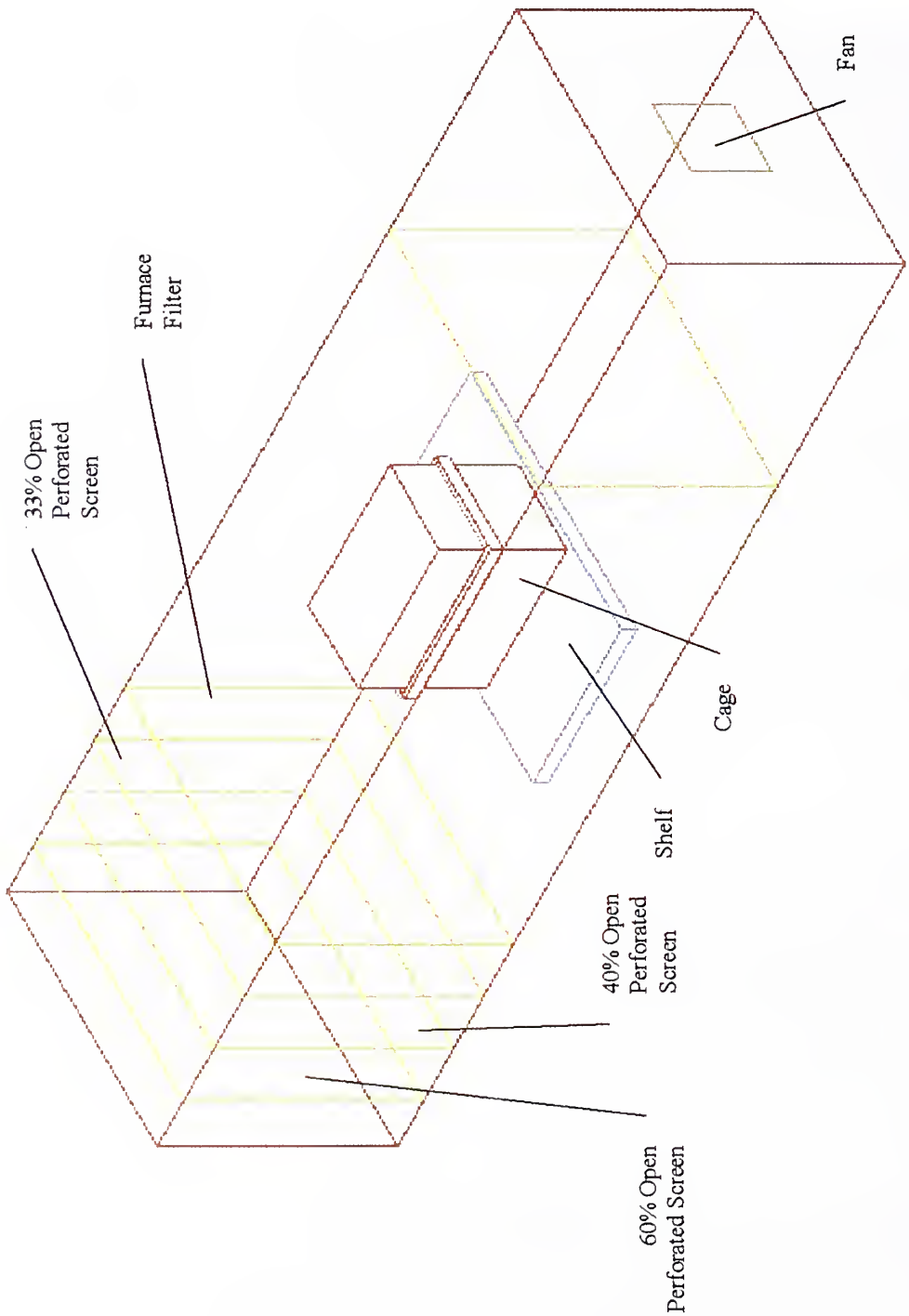


Figure 4.52 Parallel Cage Orientation CFD Model.

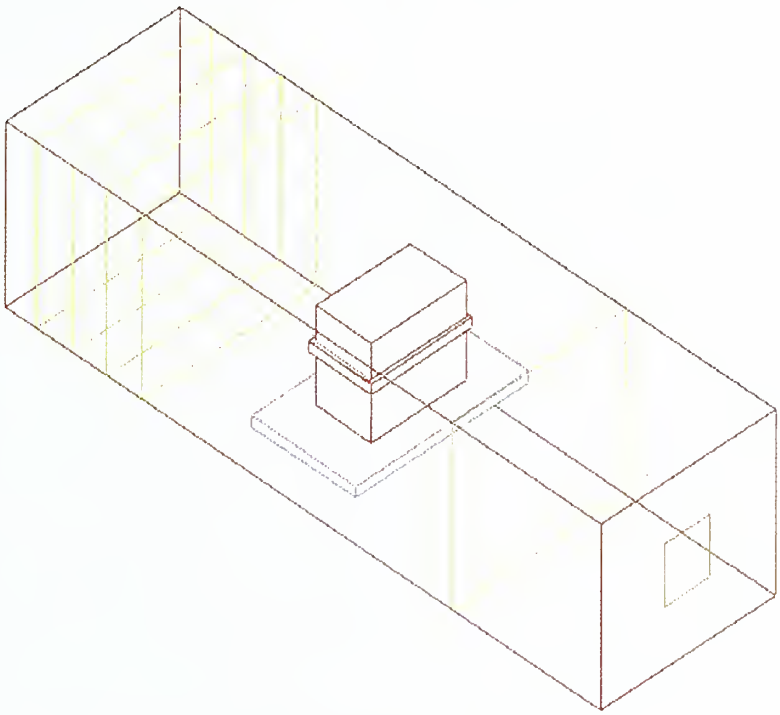


Figure 4.53 *Perpendicular Cage Orientation CFD Model.*

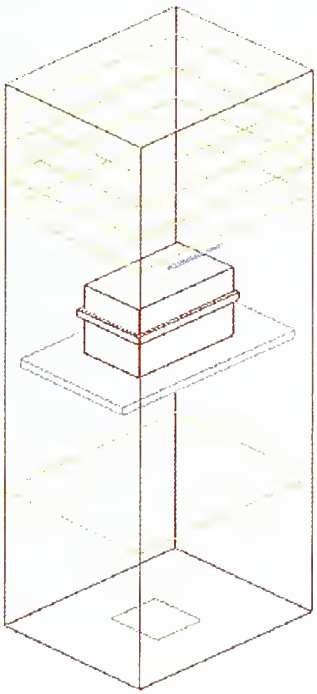


Figure 4.54 *Vertical Cage Orientation CFD Model.*

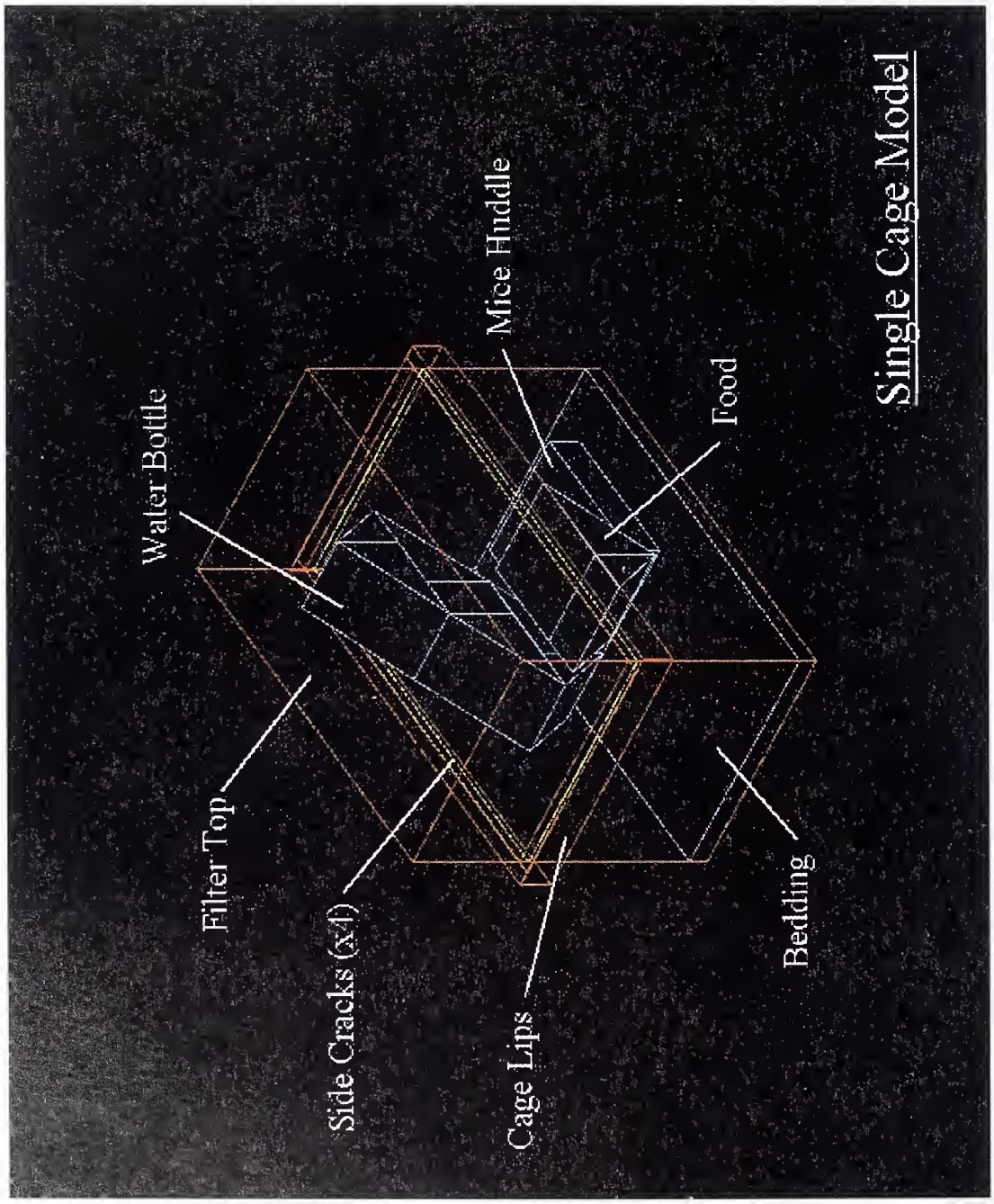


Figure 4.55 CFD Model of Single Cage. Sampling Tubes and Injection Diffuser Stones Not Shown. Mouse Heater Representation: SMO.

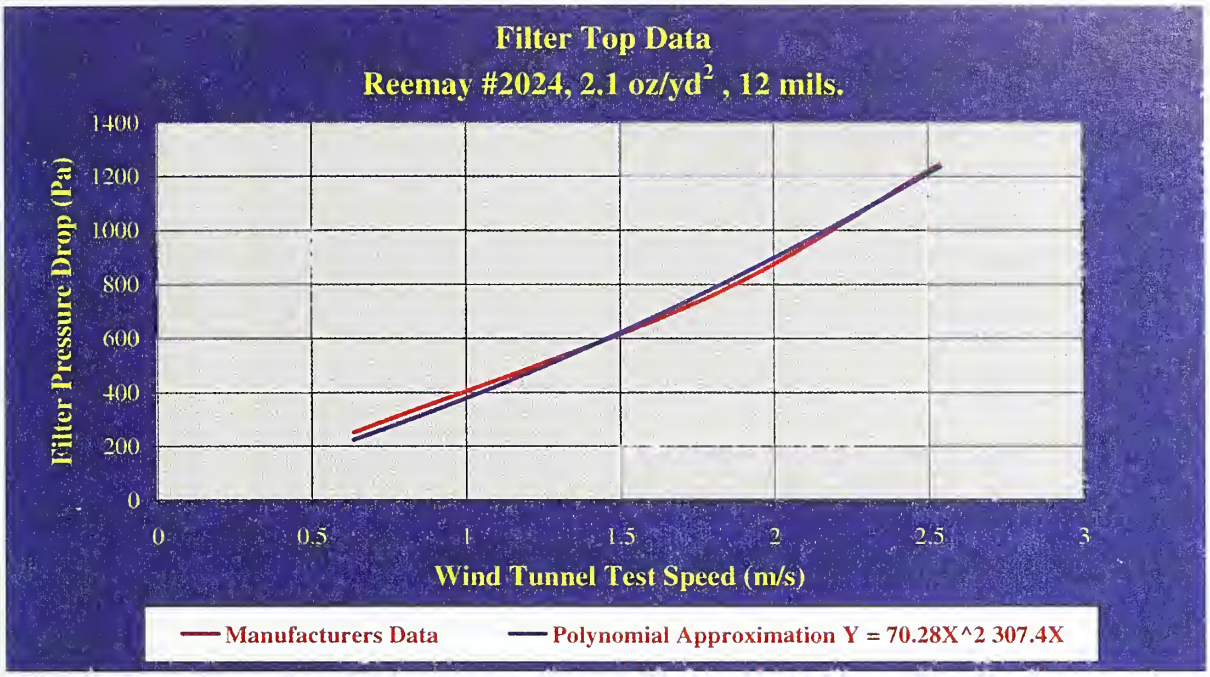


Figure 4.56 *Filter Material Test Data and Polynomial Approximation.*

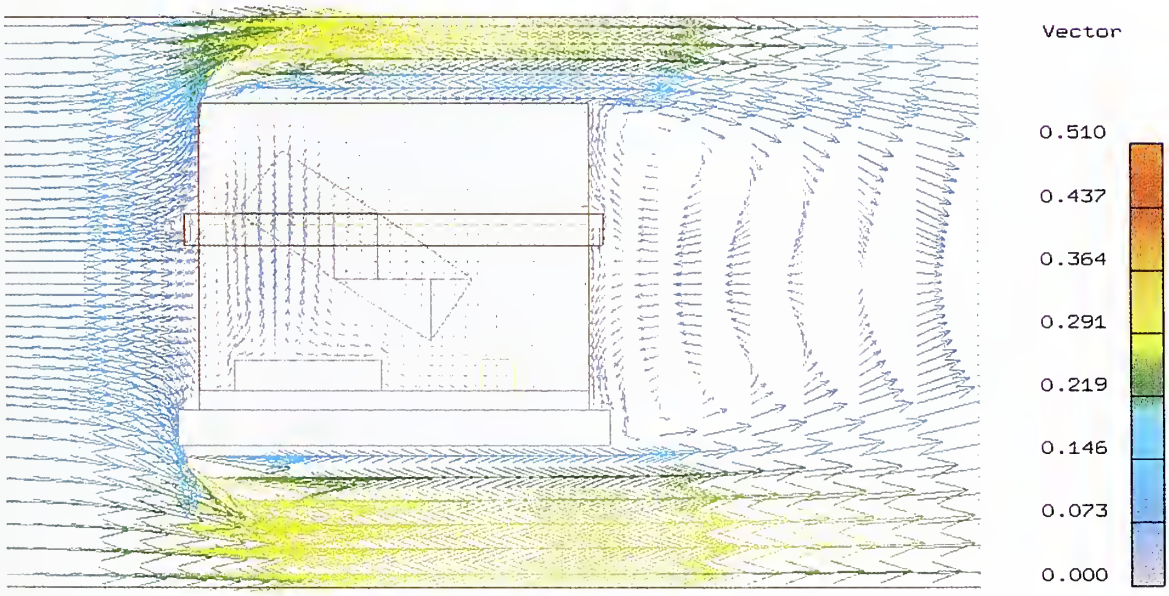


Figure 4.57 *Close-up Plot of the Vector Field at Mid-plane of Tunnel. Series Sets Six: Parallel Orientation, Heater On (SMO) 40 fpm (0.2m/s).*

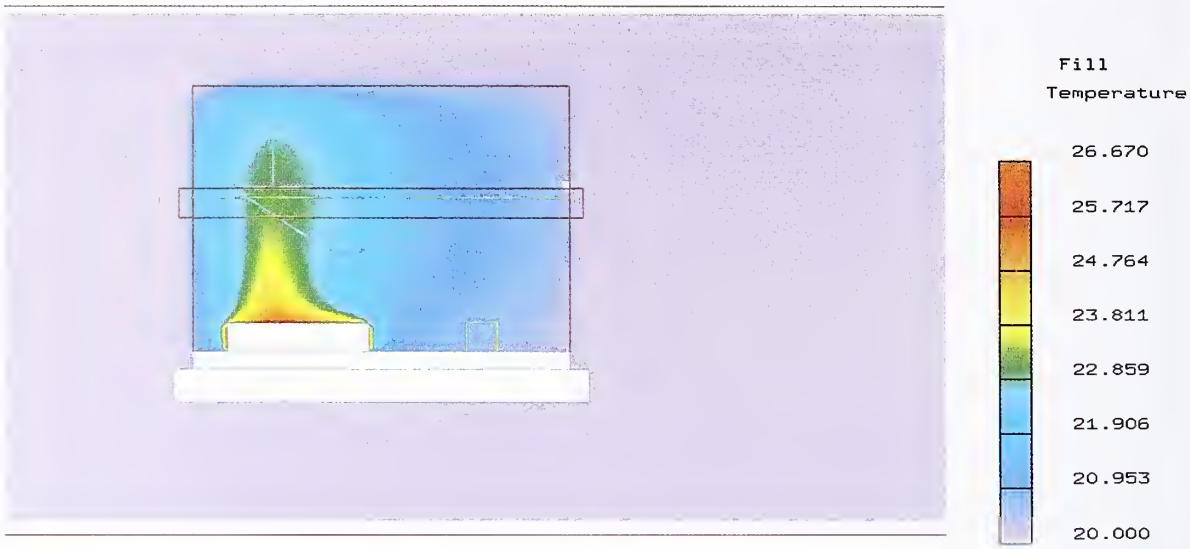


Figure 4.58 *Close-up Plot of the Temperature Field at Mid-plane of Tunnel. Series Sets Six: Parallel Orientation, Heater On (SMO) 40 fpm (0.2m/s).*

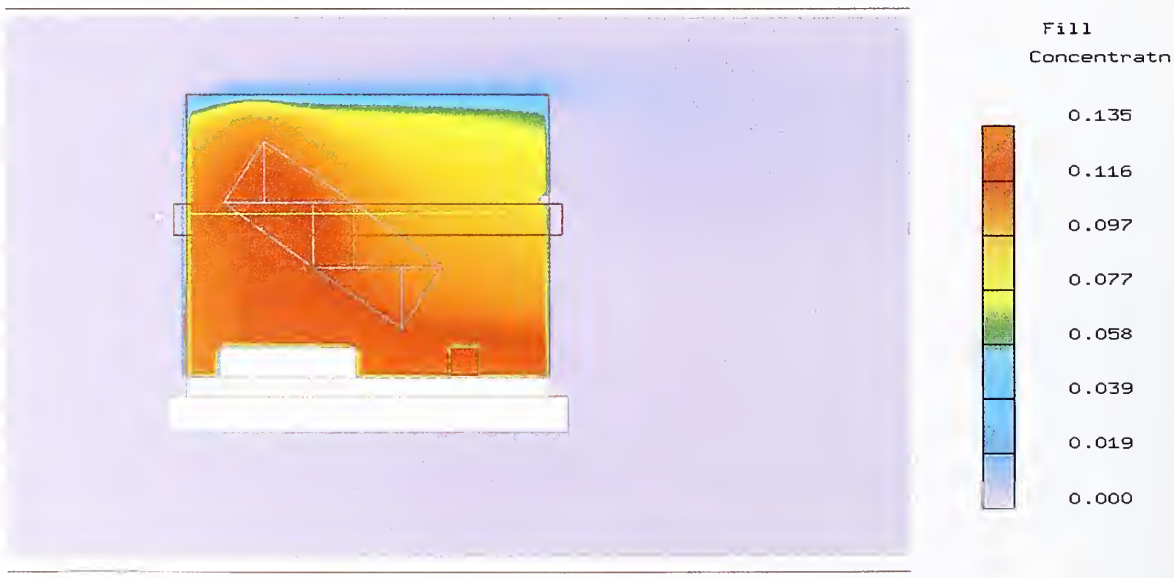


Figure 4.59 *Close-up Plot of the Concentration Field Mid-plane of Tunnel. Series Sets Six: Parallel Orientation, Heater On (SMO) 40 fpm (0.2m/s).*

4.2.2 Calibration of CFD Diffuser model against Manufacturers Data

When a diffuser is modeled using CFD it is essential to calibrate the model against manufacturer's data. This is essential because small details in the geometry of the diffuser, the method of construction, etc., can change the jet characteristics. Of course, the detailed geometry of the diffuser could itself be modeled, but the level of detail required in full room models would make the model computationally impractical. This calibration allows the modeler to identify the jet characteristics close to the face of the diffuser where they can be expected to be virtually unaffected by room conditions. The three diffuser types were: a radial diffuser; a slot diffuser; and a low induction diffuser.

4.2.2.1 Radial Diffuser

The diffuser is so named because it is designed to provide an airflow pattern that spreads in a fan shaped (or radial) fashion perpendicular to the center line of the diffuser as demonstrated in figure 4.61. The intention of this is to prevent the formation of recirculation zones either side of the diffuser that could potentially retain contaminants. For this reason, this type of diffuser/flow pattern has become increasingly popular in animal rooms, was chosen for the base case whole room simulation, and was used in the experimental empty and populated room scenarios. It should be noted however, that the sideways throw characteristics could be compromised when strong thermal effects are present.

The radial diffuser used in these simulations is as manufactured by Krueger (known in their literature as a TAD, total air diffuser) is shown in figure 4.60. The manufacturer's test facility for this diffuser measured 3.66m (12') x 3.66m (12') x 2.74m (9') high. The diffuser is located centrally in the ceiling of the test room. Two 0.30m (1') high exhausts are located at floor level. The manufacturer's data indicated the vertical and horizontal distance of the 0.25m/s (50 fpm) throw isovel (line of constant velocity) from the diffuser, that was used in the validation exercise, for various flow rates.

In the CFD representation of the test facility, advantage was made of symmetry: the right side of figure 4.61 represents the symmetry plane. The flow rate that was chosen from the manufacturer's data for validation purposes was that nearest the base case flow rate through a single radial diffuser. In particular, the base case flow rate was 270 cfm, while the nearest manufacturer's data point is for 300 cfm. Further, the effect of temperature was also considered. The data point chosen was for a 2.8 °C (5.0 °F) rise in the air temperature between the discharge and the exhaust. Heat sources were applied to the walls of the CFD model to provide such a temperature rise.

Figure 4.61 indicates that the CFD representation of the radial diffuser matches the location of the vertical and horizontal 0.25m/s (50 fpm) isovel data very well. Confidence can therefore be placed in the representation of the CFD radial diffuser in the animal facility simulations.

4.2.2.2 Slot Diffuser

A typical slot diffuser is shown in figure 4.62. The slot diffuser provides high shear flow conditions at inlet, that result in high entrainment of the surrounding air into the jet flow, and consequently highly mixed conditions.

The manufacturer's (Gilberts) test facility in this instance measured 5m x 7m x 3m high (16.4' x 22.97' x 9.84'). The diffuser is centrally located in the ceiling of the test room. The manufacturer's data indicated the vertical distance of the 0.25 m/s (50 fpm) throw isovel from the diffuser, that was used in the validation exercise, for various flow rates.

In the CFD representation, the flow rate that was chosen from the manufacturer's data for validation purposes was that nearest the base case flow rate through a single radial diffuser. In particular, the base case flow rate was 270 cfm, while the nearest manufacturer's data point was 350 cfm.

Figure 4.63 demonstrates that the CFD representation of the slot diffuser matches the location of the 0.25 m/s (50 fpm) isovel data very well. Confidence can therefore be placed in the representation of the CFD slot diffuser model in the animal facility simulations.

4.2.2.3 Low Induction Diffuser

A typical low induction diffuser is shown in figure 4.64. The low induction diffuser provides low shear flow conditions at inlet that result in low induction of the surrounding air into the jet flow. This diffuser therefore provides a solid column of clean air, purging the space of contaminants immediately below it. The disadvantage is then that large recirculations are formed either side of the diffuser jet.

The manufacturer's (Gilberts) test facility in this instance measured 5m x 7m x 3m high (16.4' x 22.97' x 9.84'). The diffuser is centrally located in the ceiling of the test room. The manufacturer's data indicated the vertical distance of the 0.25 m/s (50 fpm) throw isovel from the diffuser, that was used in the validation exercise, for various flow rates.

In the CFD representation, the flow rate that was chosen from the manufacture's data for validation purposes was that nearest the base case flow rate through a single radial diffuser. In particular, the base case flow rate was 270 cfm, while the nearest manufacturer's data point was 325 cfm.

Figure 4.65 demonstrates that the CFD representation of the low induction diffuser matches the location of the 0.25 m/s (50 fpm) isovel data very well. Confidence can therefore be placed in the representation of the CFD low induction diffuser model in the animal facility simulations.

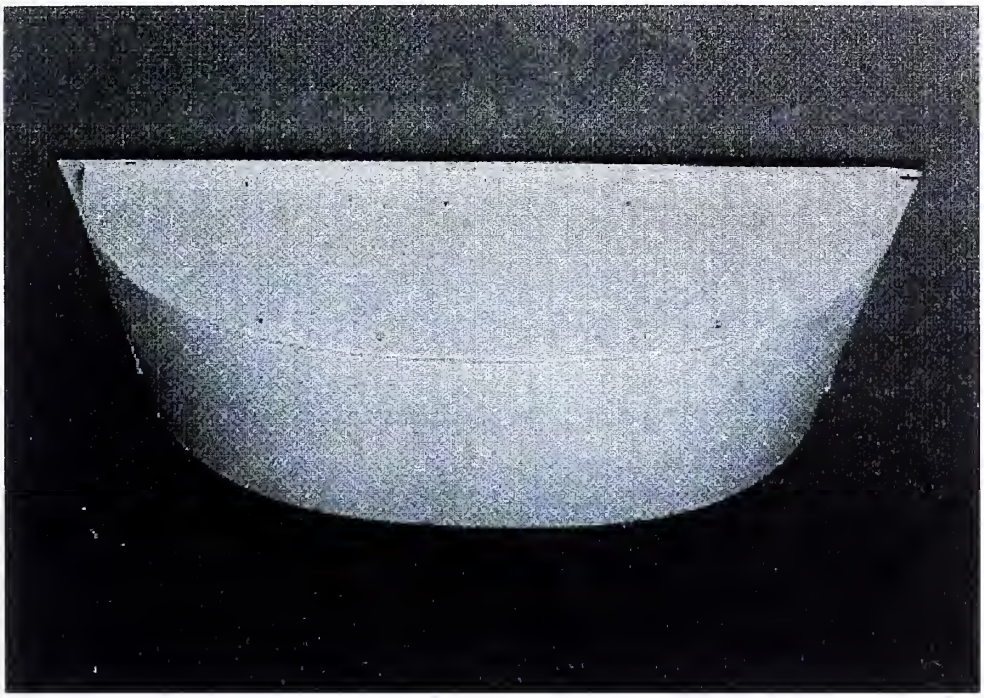


Figure 4.60 Radial Diffuser.

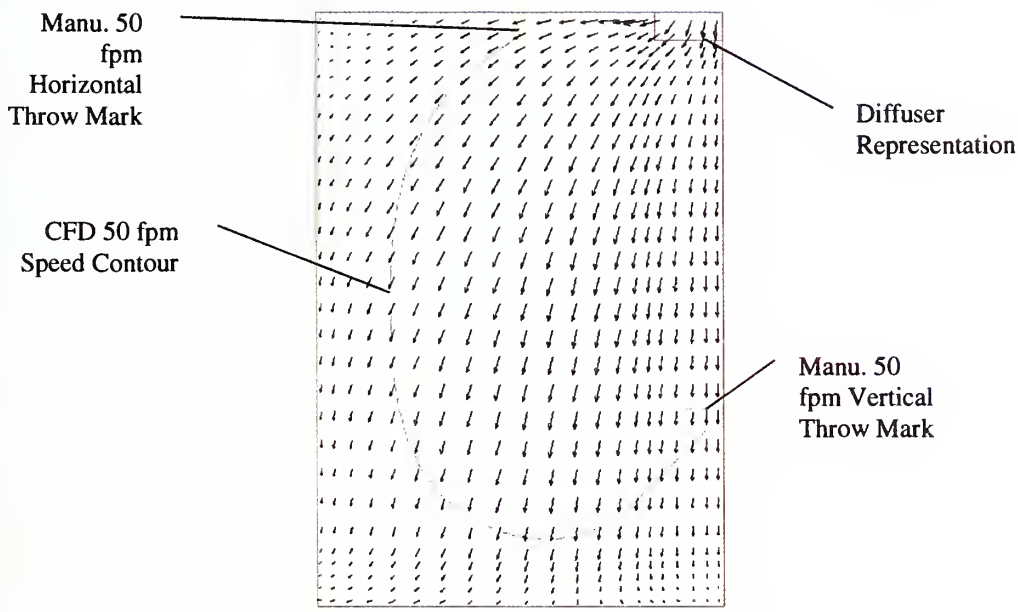


Figure 4.61 Comparison of CFD and Manufacturers Data for Radial Diffuser.

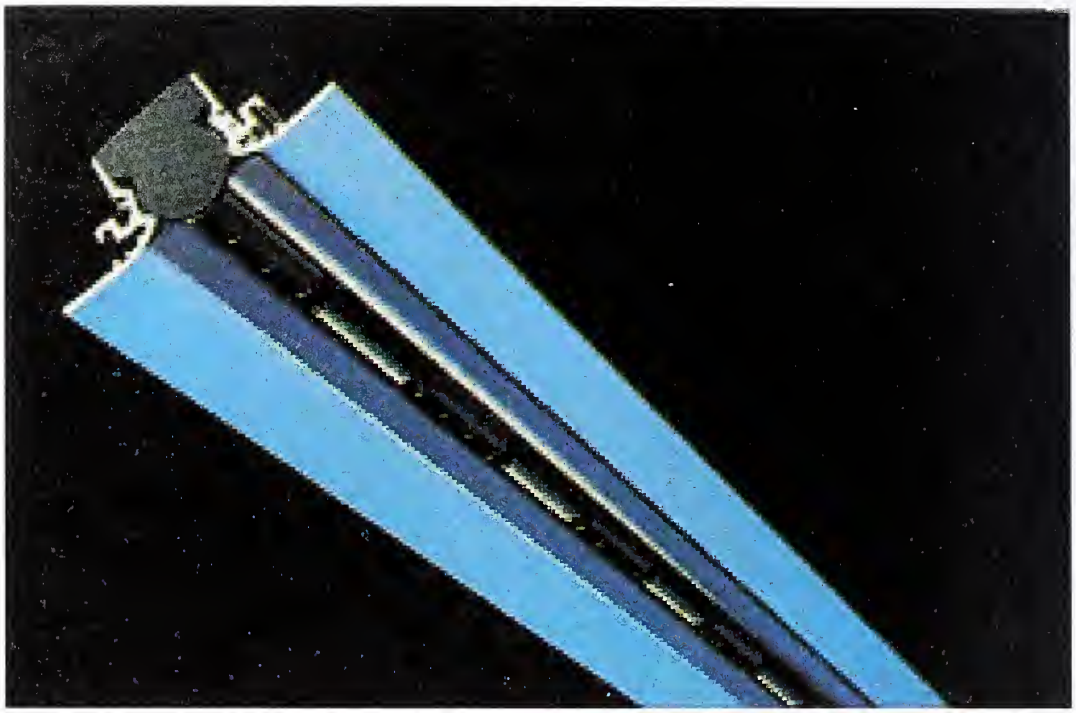


Figure 4.62 Slot Diffuser.

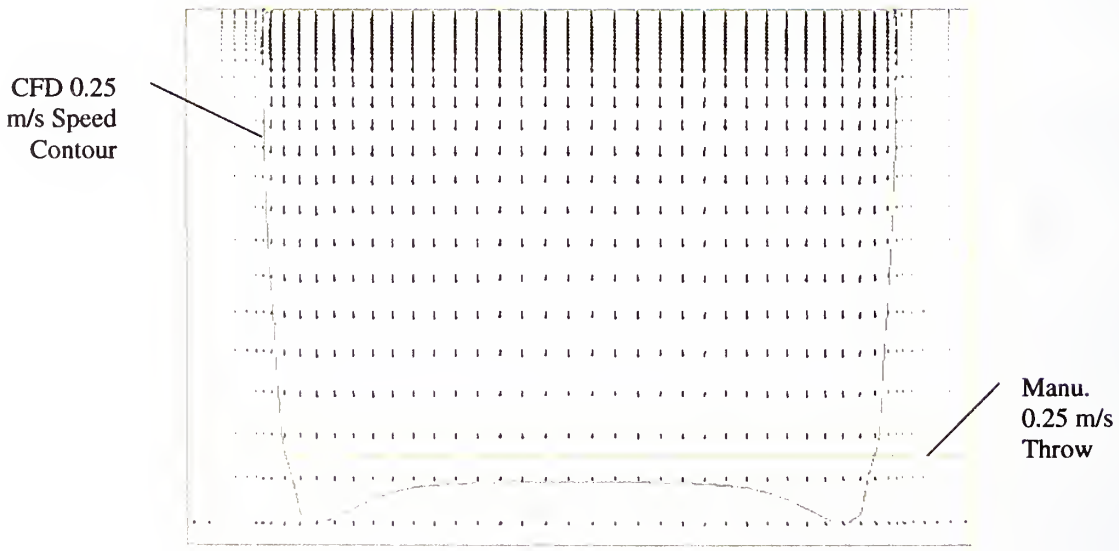


Figure 4.63 Comparison of CFD and Manufacturers Data for Slot Diffuser.

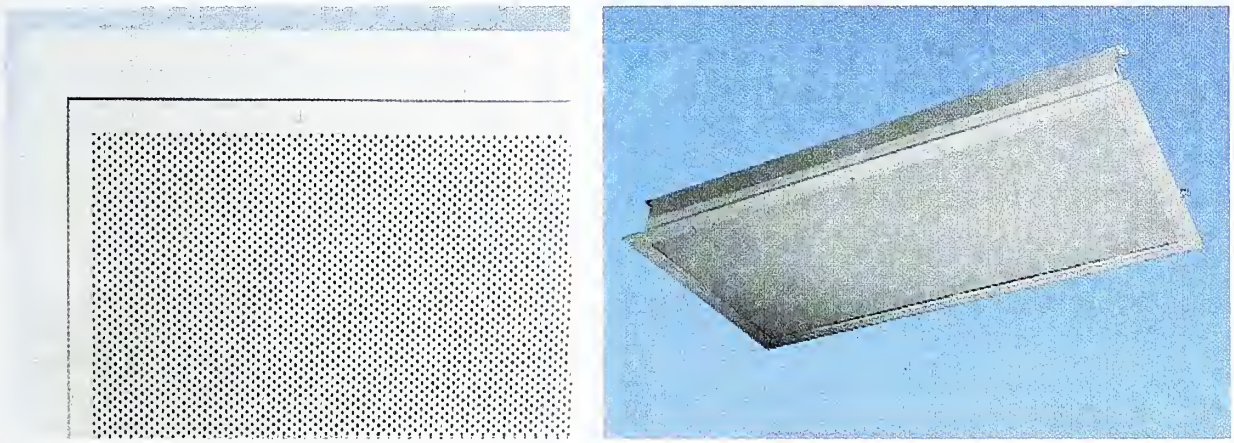


Figure 4.64 *Low Induction Diffuser.*

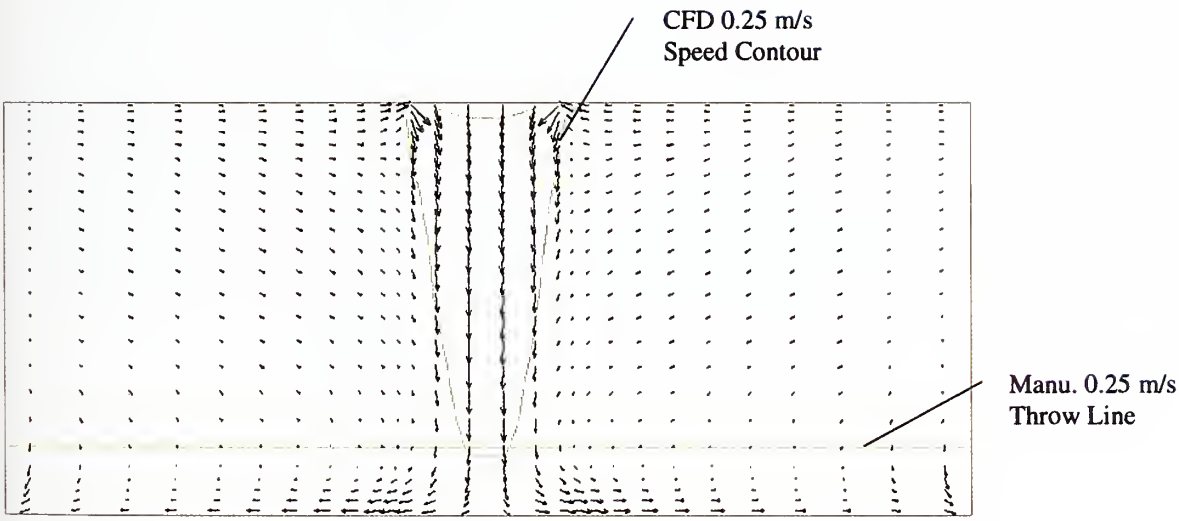


Figure 4.65 *Comparison of CFD and Manufacturers Data for Low Induction Diffuser.*

4.2.3 Room Condition

4.2.3.1 CFD Simulations

Two CFD models were constructed to replicate the experimental testing room scenarios as closely as possible. Isometric views of the two rooms are shown in figures 4.66 and 4.67. The overall size of the solution domain of both models was high 2.44m x 3.66m x 2.44m (8' x 12' x 8'). The 0.61m x 0.57m (24" x 22.5") centrally located radial diffuser was constructed using a combination of a supply and a series of planar resistances, with the loss coefficients for the planar resistances set such that the representation matched the available manufacturer's data (see section 4.2.2). The supply was specified to provide a flow rate of 128 cfm (7.27e-02 Kg/s).

The 0.30m x 0.30m (12" x 12") exhaust, modeled using an extract, was located 0.20m (8") from the north and west walls, and was specified to exhaust 102 cfm (5.8e-02 Kg /s). The mass imbalance was accounted for through a 6.4e-2m (¼") crack at the bottom of the 0.91m x 2.13m (3' x 7') door, that was centrally located on the north wall.

In the populated room case, the 0.61m x 0.61m x 0.81m (24" x 24" x 32") sink, located in the NE corner of the room, was modeled using a solid rectangular block. The sink recess was not modeled.

The shelves of the 0.61m x 1.83m x 1.52m (24" x 72" x 60") rack were modeled using 1.27e-2m (0.5") thick rectangular blocks. The top shelf was located 1.52m (60") above the floor, and the experimental shelf-to-shelf distance of 0.28m (11") was maintained. The sides of the 0.27m x 0.16m x 0.21m (10.7" x 6.38" x 8.39") shoebox cages were modeled using thin plates, with conductivity and thickness of the plate set to that of the polycarbonate. The water bottle in the cage was constructed from a series of rectangular blocks and triangular prisms: the volume of the water bottle was maintained compared with the physical bottle. The rack was modeled as a planar resistance, with the loss coefficient set to 0.25, corresponding to a free area ratio of 0.85 (Idelchik (1989)). The heater was modeled using a fixed flux rectangular block, with the block specified to dissipate 2.42 W. The diffuser stones were modeled using volume sources, with the injection rate of the CO_2 concentration set to 990 mL/min (3.01 E-5 kg/s) total, or 7.86 mL/min per cage (2.39 E-7 kg/s).

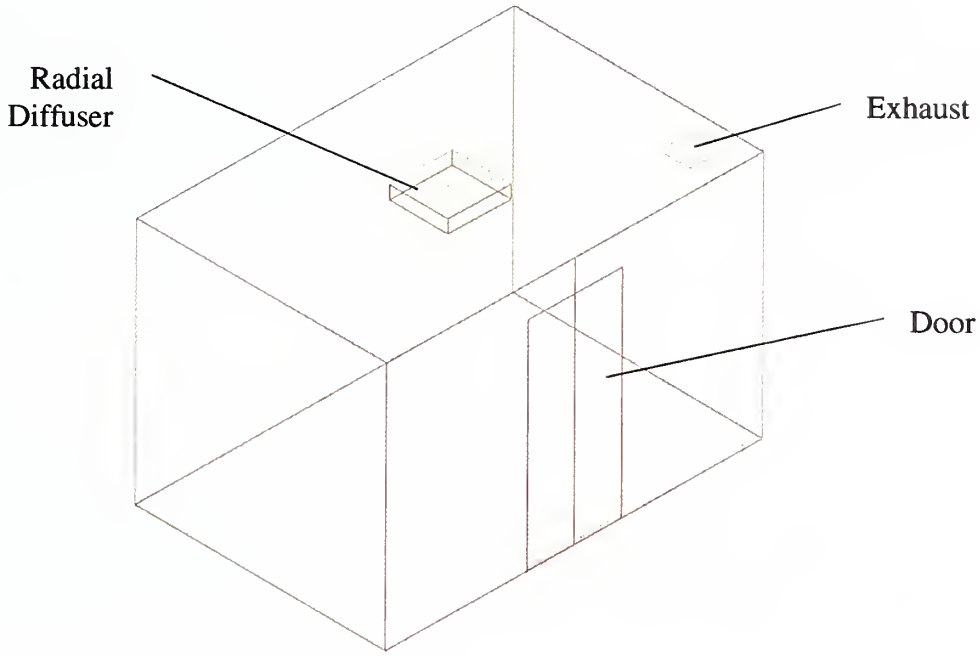


Figure 4.66 *CFD Model Empty Room.*

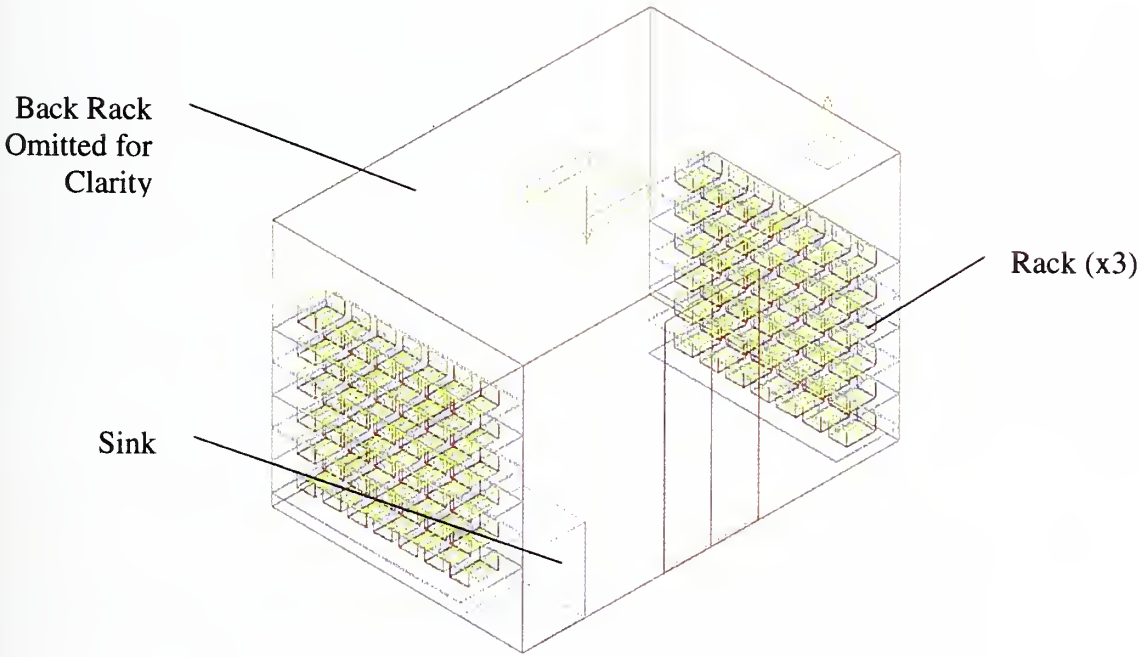


Figure 4.67 *CFD Model: Populated Room.*

4.2.3.2 Comparison of Experimental Data and CFD Results

This section compares data for two different room configurations, air velocity and temperature for an empty room, and air velocity, temperature and concentration for a stocked room. The challenge with this task largely relates to the measurement of the predominantly low air velocities. This is the case for two reasons. Firstly, the predominant air velocities are low and quite difficult to measure. Secondly, but probably more importantly, small temperature effects or infiltration can easily cause air currents of the order of the air speeds of interest. As a result CFD provides a good understanding of the key flow patterns and comparison is most easily made between the scalar quantities such as temperature and concentration. These are compared for the stocked or populated room

4.2.3.2.1 Empty Room

Due to the large amount of data, only two planes are considered for this experimental scenario. The two planes are plane 1, that is the experimental plane 0.15m (6") from the north wall and so is near the corner exhaust, and plane 8, that is experimental plane 1.22m (48") from the north wall, and so is located mid-way through both the room and the supply diffuser. For a full explanation of the experimental plane locations, see appendix I: section 4.3.2.

Speed Results

The fill plot of the experimental mean air velocity (speed) at experimental plane 1 (i.e. the plane 0.15m (6") from the north wall) is displayed in figure 4.68. Note that the left-hand side of the plot indicates the east wall, and the key range is between 0 and 40 fpm (0.2m/s). The plot clearly shows the locations of the various measurement zones. In particular, the upper left-hand side of the plot shows a region of relatively uniform speed flow, with the magnitude of the airflow velocity being typically around 0.15m/s (30 fpm) and higher. The spots of white in this region indicate velocity measurements that are higher than this: the peak velocity at this plane is 0.28m/s (55 fpm). This region can be clearly seen to be the zone 1, upper east measurement region (see appendix I: section 4.3.2). Also in this plot, the upper right corner of the plot should show a clear increase in velocity near the ceiling, as this plane is close to the corner exhaust of the room. There is no such feature present in the plot. Moving further into the room, the fill plot of the experimental speed field at experimental plane 8 (i.e. 1.22m (48") from the north wall) is displayed in figure 4.69. The white region at the center near the ceiling is the location of the diffuser, with the speeds here being above 0.20m/s (40 fpm). This is an expected feature. However, there are several spots within the plot that are either above or near 0.20m/s (40 fpm), that are well away from the diffuser region. In both plots, the appearance of the high speed sections in the experimental data is unexpected. In particular, appendix I: section 4.1.2 states that, based on theoretical considerations, the air velocity should not exceed 0.11m (22 fpm) outside the jet zone (within 0.30m (12") of the central diffuser), unless there is disturbance to the airflow. As plane 1 is furthest from the jet zone, and the room is fundamentally empty apart from the supply and exhaust, the higher speed values are subject to doubt.

The fill plot of the speed field at plane1 for the CFD simulation is shown in figure 4.70. The plot does not show the same blocks of high speed that are shown in the equivalent experimental plot. Further, the plot also indicates the clear acceleration of air towards the exhaust located in the upper right corner of the plot, that is an expected feature at this plane. The fill plot of the speed field at plane 8 for the CFD simulation is shown in figure 4.71. The plot shows a more consistent flow field associated with the diffuser than the experimental data. In particular, although higher speed flow exists close to the diffuser itself, this flow is quickly slowed as air is entrained into the jets. There are no spots of higher velocity away from this region as there are in the experimental plot.

Temperature Results

The fill plot of the experimental temperature field at experimental plane 1 (i.e. the plane 0.15m (6") from the north wall) is shown in figure 4.72. Note that the left-hand side of the plot indicates the east wall, and that the key range is between 21.1 to 25.0 °C (70.0 and 77.0 °F). The plot clearly shows the demarcation of the various experimental measurement zones. In particular, there are sections of the plot that show same color blocks that indicate regions of approximately the same temperature: others sections show different temperature regions. The reason for this is that the experimental data in the individual zones were taken with different wall surface conditions, as outlined in appendix I: section 4.3.1. This effect is even more marked on consideration of figure 4.73, that displays the fill plot of experimental temperature field at experimental plane 8 (i.e. the plane halfway through the room, 1.22m (48") from the north wall).

However, in the CFD simulation, the boundary walls were defined as being at an average surface temperature. As a result, the fill plots for the temperature fields do not exhibit the dominant effect of the wall surface temperature. Figure 4.74 displays the fill plot of the temperature field at plane 1 (i.e., the plane 0.15m (6") from the north wall). As the flow field exhibits essentially well mixed, isothermal conditions here, the temperature field shows relatively little variation. At the center plane of the room, plane 8 (i.e., the plane 1.22m (48") from the north wall), the shape of the incoming diffuser air is evident, as shown in figure 4.75.

Despite the apparent differences in the two sets of data, the levels of difference between the data is reasonable, as demonstrated in tables 4.2.13 and table 4.2.14. In particular, the average difference at plane 1 is around 11.6 percent, while that at plane 8 is around 16.8 percent. These are well within normally accepted experimental uncertainty.

Discussion and Conclusions

The above comparison demonstrates that reasonable agreement was obtained with regards to the temperature field, while the experimental speed field displayed several features and values that were subject to doubt.

The experimental temperature and speed fields highlight the difficulty of maintaining isothermal conditions in a test facility, despite the adherence to rigorous experimental protocol. This has a

significant impact on the airflow and temperature distributions. This is particularly important when using a diffuser of the radial type since they have inherently low momentum, so the jet is easily affected by small, induced air currents.

The problems are clearly identified by the fact that measured values of air speed are well in excess of the theoretical limit of 0.11m/s (22 fpm) well away from the diffuser jet (see appendix I: section 4.1.2). The CFD results only show these larger air speeds where they would be expected – close to the supply air diffuser and the room exhaust. The advantage of the computational fluid dynamics approach is that, by definition, the predicted values for the parameters in the analysis have to be consistent since the approach is based on the fundamental laws for the conservation of mass, momentum, and energy. The experimental approach does not benefit from any such luxury since the measurements are each independently recorded by parameter and by location. Air velocities of the low speeds seen in a room (in this case typically below 0.10 m/s (20fpm)), for example, are inherently difficult to measure for several reasons:

- The low velocities are very susceptible to fluctuations as well as variations in the boundary conditions over the period of the experiment. Extending the sampling period for individual points to obtain a more representative average can be counterproductive since it increases the total period of the experiment and makes it more difficult to maintain the boundary conditions for the experiment.

- The constant temperature thermistor based sensing head (used in hot film anemometers) becomes inaccurate at low speeds because the heating of the head causes local air velocities of a similar order.

- The presence of the measurement equipment, and any traversing equipment (see figures 4.32 and 4.33) can influence the local velocities.

The scalar quantities such as temperature and concentration are easier to measure, and as this section (and the following section, section 4.2.3.2.2 show) shows good correlation can be seen between the measured and predicted data.

Given that the predictions of temperature and concentration are good then, by the laws of conservation the air velocities must also be well predicted, with the discrepancies between measured and predicted data being accounted for by difficulty in measurement outlined above.

It should be also be remembered that the CFD model of the radial diffuser was found to accurately predict the manufacturer's throw data (see section 4.2.2), and so a good degree of confidence should be place in the CFD representation of the diffuser.

As far as the temperature measurements are concerned, the experimental data plots, for example, figure 4.72, highlight the difficulty in maintaining isothermal conditions within test facilities. In this example, the differing boundary wall temperatures have a marked impact on the internal room temperatures.

Table 4.2.13 Table of percent Difference between Experimental and CFD Temperature Data at Plane 1 (0.15m (6") from North Wall)

Dist. From Floor (")	Distance From West Wall (")											
	138	132	126	120	114	108	102	96	90	84	78	72
90	11.5	14.1	13.2	11.4	13.7	24.2	15.1	18.2	16.6	26.1	8.7	2.8
84	8.6	15.8	14.2	13.5	14.2	20.0	17.2	18.0	16.9	25.8	9.9	1.2
78	7.1	14.7	15.7	10.6	13.7	19.9	18.1	20.8	22.2	23.9	10.9	1.6
72	7.0	12.8	10.6	8.3	12.4	19.4	15.8	20.7	23.6	14.2	6.2	4.4
66	4.1	10.5	9.7	7.0	10.9	17.4	15.5	19.5	22.2	12.9	8.7	13.4
60	2.4	8.4	8.6	10.8	11.3	18.4	13.8	17.4	19.0	9.9	7.8	3.2
54	2.5	7.2	7.2	8.3	10.2	17.2	8.4	15.9	17.5	9.0	7.1	0.9
48	1.8	7.0	4.5	8.4	9.6	17.4	6.4	15.0	14.2	4.4	8.2	0.5
42	1.4	7.5	4.5	5.4	9.8	17.0	8.4	16.6	15.3	4.2	9.9	0.7
36	1.7	8.4	4.6	7.0	11.9	17.8	6.6	13.7	12.0	4.0	13.1	3.1
30	2.5	8.0	5.8	8.3	12.8	16.0	8.5	14.9	15.0	4.7	12.4	3.6
24	19.2	19.1	23.4	19.0	36.9	29.5	25.5	28.8	29.0	22.2	8.2	12.4
18	21.6	23.6	19.6	19.7	37.0	29.5	20.9	24.8	23.6	22.1	8.8	15.5
12	20.2	26.8	18.4	17.8	36.8	28.8	20.4	25.8	21.8	21.8	10.3	15.2
6	19.8	23.6	18.9	18.6	38.6	30.4	20.5	26.3	22.8	21.5	8.9	15.0

Dist. From Floor (")	Distance From West Wall (")										
	66	60	54	48	42	36	30	24	18	12	6
90	3.9	3.0	4.3	8.3	8.2	4.5	3.3	4.9	3.9	7.4	2.3
84	4.1	0.9	5.0	10.3	4.5	4.6	6.4	6.1	6.1	7.7	1.4
78	0.8	1.4	2.0	7.8	7.2	8.0	6.0	4.4	8.3	6.4	0.2
72	1.2	0.2	2.3	6.4	8.9	7.4	3.5	5.1	8.3	4.7	0.1
66	0.5	0.4	3.9	11.6	3.0	7.6	5.7	1.2	8.0	5.8	0.9
60	1.2	1.0	6.2	14.3	4.2	7.6	5.6	0.8	6.9	4.1	0.9
54	2.8	1.4	3.1	8.8	11.6	9.4	9.0	6.6	8.8	3.3	2.5
48	1.5	1.0	2.6	6.2	5.8	4.7	7.4	11.7	9.7	5.8	1.8
42	1.9	2.8	1.0	6.9	3.6	3.1	6.9	10.6	10.6	7.7	4.0
36	4.6	6.8	2.5	4.5	6.5	4.1	7.3	7.4	13.9	8.2	5.3
30	2.5	6.4	3.3	4.2	6.4	7.1	9.1	0.5	15.7	15.8	6.5
24	9.1	11.9	23.5	20.9	18.2	22.8	22.8	16.0	21.7	22.2	18.8
18	13.5	11.2	26.9	22.7	15.7	20.1	17.2	17.0	19.0	23.0	18.5
12	10.2	11.7	26.7	22.1	13.8	18.8	19.2	17.9	17.5	21.6	19.0
6	11.4	12.7	23.9	28.6	12.4	11.7	14.0	10.1	19.3	23.2	20.4

Table 4.2.14 Table of percent Difference between Experimental and CFD Temperature data at Plane 8 (1.22m (48") from North Wall)

Dist. From Floor (")	Distance From West Wall (")											
	138	132	126	120	114	108	102	96	90	84	78	72
90	23.7	28.7	18.5	25.2	17.1	22.5	14.7	17.3	19.1	14.2	0.8	2.2
84	26.9	31.4	24.3	41.9	26.9	26.9	18.2	21.8	24.6	19.9	2.6	0.9
78	25.6	26.7	22.6	22.3	25.9	23.1	19.1	23.7	26.6	22.7	0.3	7.2
72	25.4	26.6	22.5	22.5	26.0	23.4	19.4	24.0	27.1	23.2	4.4	11.8
66	20.9	24.8	20.3	20.6	22.0	21.1	20.6	23.0	25.8	20.0	12.5	17.9
60	19.2	24.3	20.7	22.4	26.1	25.0	20.2	27.0	27.5	21.2	11.6	16.0
54	19.6	25.0	19.2	21.9	24.3	23.0	18.1	26.1	27.9	20.7	4.4	8.8
48	18.0	25.5	19.1	18.8	20.7	22.9	19.6	23.5	26.7	26.9	4.6	13.5
42	18.2	25.6	24.0	22.7	25.1	25.6	20.2	25.5	29.9	25.2	0.3	7.3
36	17.8	25.9	24.4	22.4	29.0	27.0	22.4	27.3	28.5	22.0	0.2	7.5
30	19.1	25.5	21.3	22.5	27.9	27.6	23.1	30.5	32.3	25.4	1.2	6.8
24	8.8	13.8	9.9	8.1	22.5	18.4	17.9	15.1	17.6	18.4	15.1	20.9
18	8.0	15.7	8.3	7.6	22.5	19.0	16.2	20.5	24.2	14.7	15.1	23.9
12	8.0	13.5	6.3	7.6	20.8	21.6	17.4	17.5	19.0	11.9	13.6	22.0
6	6.7	6.7	4.4	5.2	19.1	19.7	12.4	16.1	20.5	14.5	16.0	23.5

Dist. From Floor (")	Distance From West Wall (")										
	66	60	54	48	42	36	30	24	18	12	6
90	3.3	2.4	3.2	6.5	4.8	7.9	13.2	18.3	2.1	0.7	1.2
84	0.6	0.8	2.4	5.5	5.0	8.7	12.9	19.5	2.9	0.2	1.1
78	3.5	4.1	5.8	8.4	8.2	11.4	15.5	23.2	3.5	0.4	1.5
72	8.2	9.5	10.9	13.6	12.6	15.5	20.0	27.3	3.5	0.2	1.3
66	16.0	17.5	18.4	20.3	17.7	21.7	24.7	28.8	3.6	0.6	2.3
60	11.7	13.5	13.4	18.1	16.0	20.3	24.7	25.7	4.4	1.5	4.3
54	6.2	7.7	11.3	18.4	15.2	20.5	25.2	27.0	5.5	2.3	5.7
48	4.7	8.8	13.0	20.5	16.6	20.5	24.4	26.3	7.8	5.0	7.3
42	3.3	6.0	13.0	20.2	14.9	19.6	22.3	23.7	9.1	5.8	8.7
36	3.4	5.6	12.4	17.1	11.9	16.1	19.2	20.5	9.6	7.1	7.9
30	2.4	4.1	10.7	15.4	9.3	13.7	16.8	19.2	8.5	7.4	9.5
24	18.4	16.9	21.3	23.8	20.8	20.6	28.4	28.8	24.4	27.1	38.1
18	20.9	14.8	22.8	22.3	17.6	19.9	25.8	25.2	21.9	28.4	27.6
12	15.7	15.6	25.8	22.8	18.9	18.6	23.7	24.5	20.6	21.7	-
6	17.4	15.7	23.8	23.1	19.9	18.7	22.3	24.0	20.2	18.0	28.5

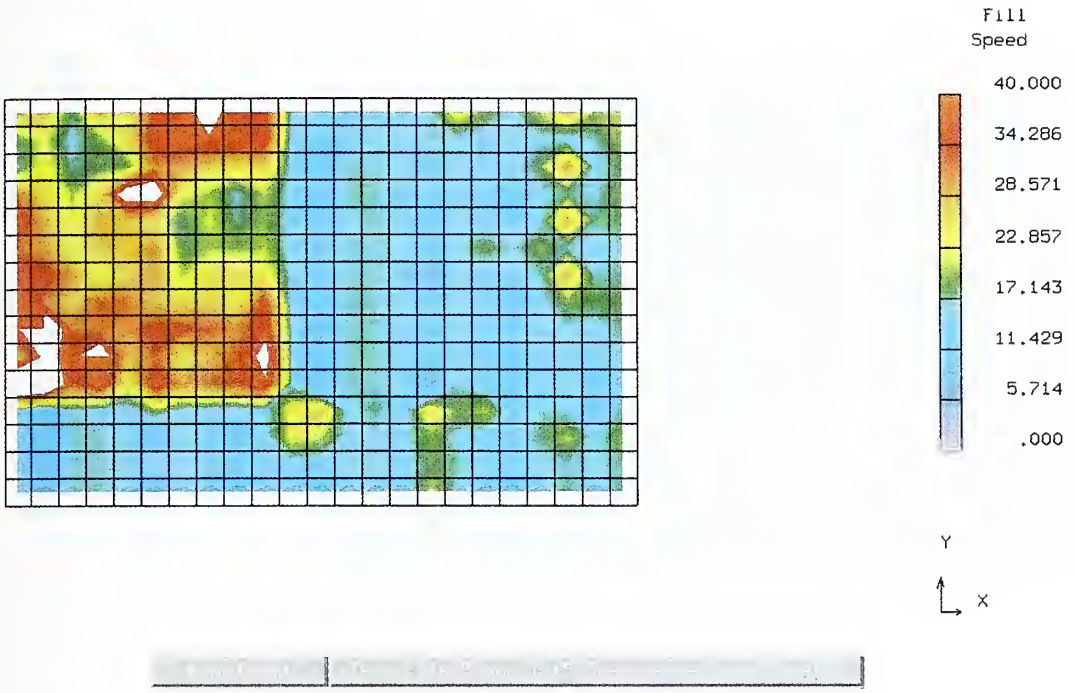


Figure 4.68 *Fill Plot of Speed Field (Experimental) at Plane 1 (Plane (0.15m (6") from North Wall). Empty Room Case.*

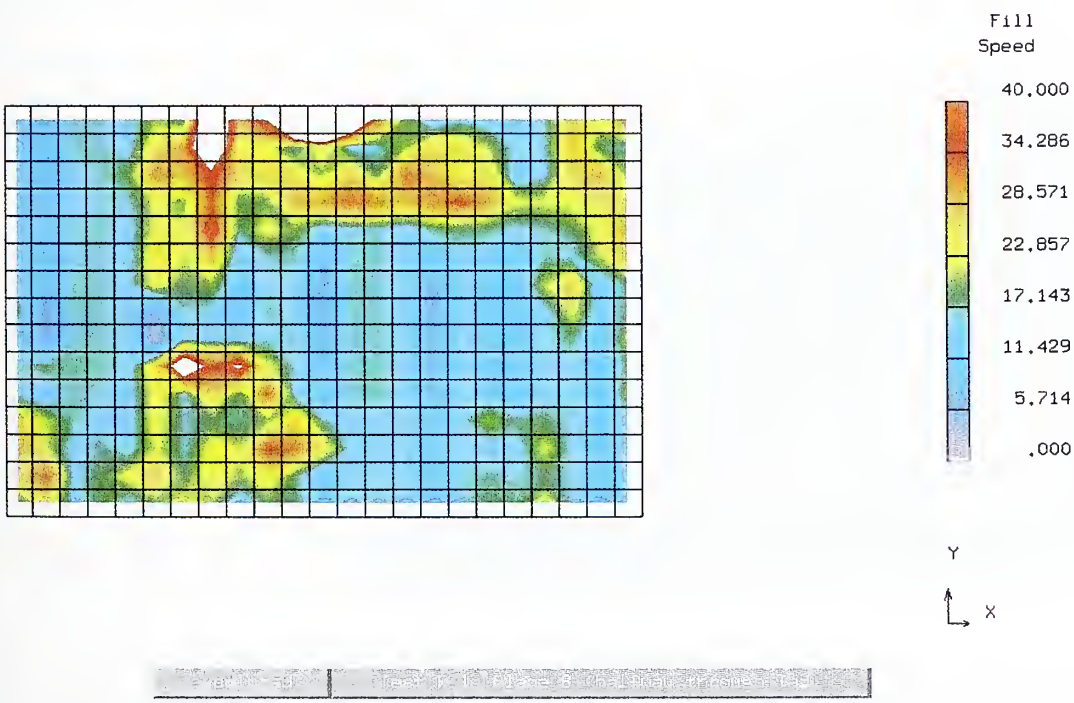


Figure 4.69 *Fill Plot of Speed Field (Experimental) at Plane 8 (Plane 1.22m (48") from North Wall). Empty Room Case.*

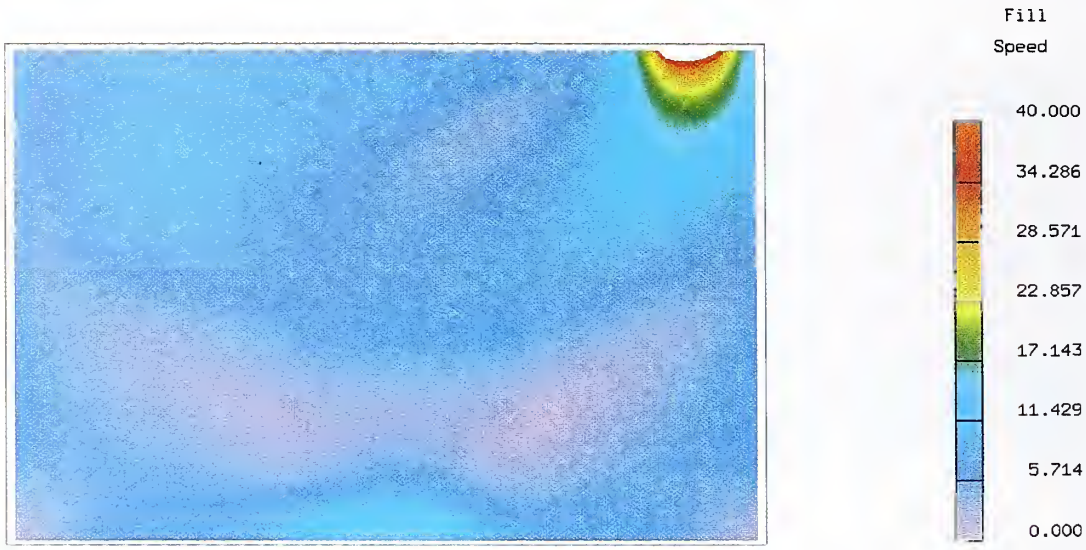


Figure 4.70 *Fill Plot of Speed Field (CFD) at Plane 1 (Plane 0.15m (6") from North Wall). Empty Room Case.*

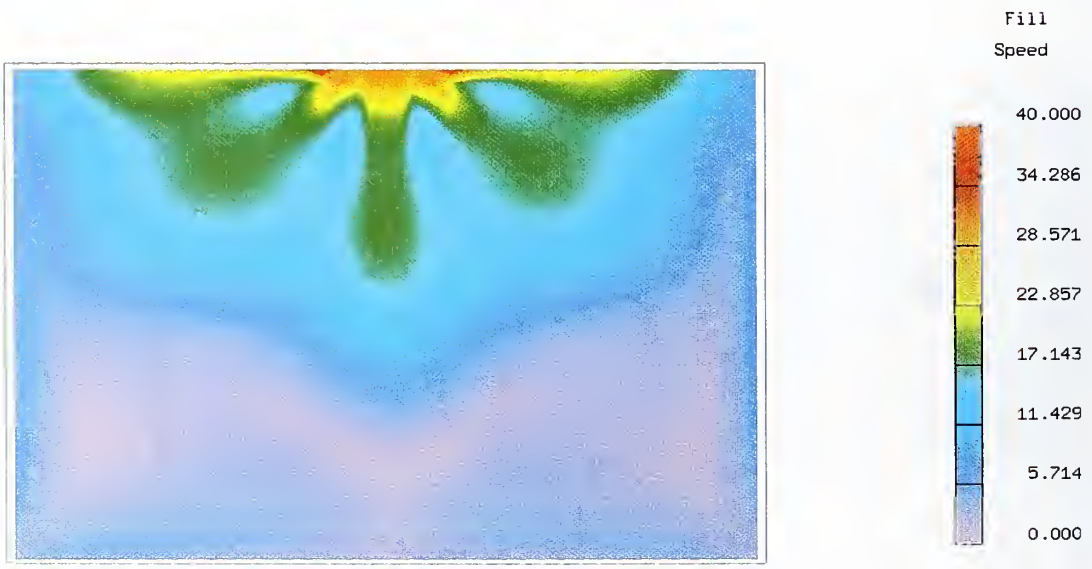


Figure 4.71 *Fill Plot of Speed Field (CFD) at Plane 8 (Plane 1.22m (48") from North Wall). Empty Room Case.*

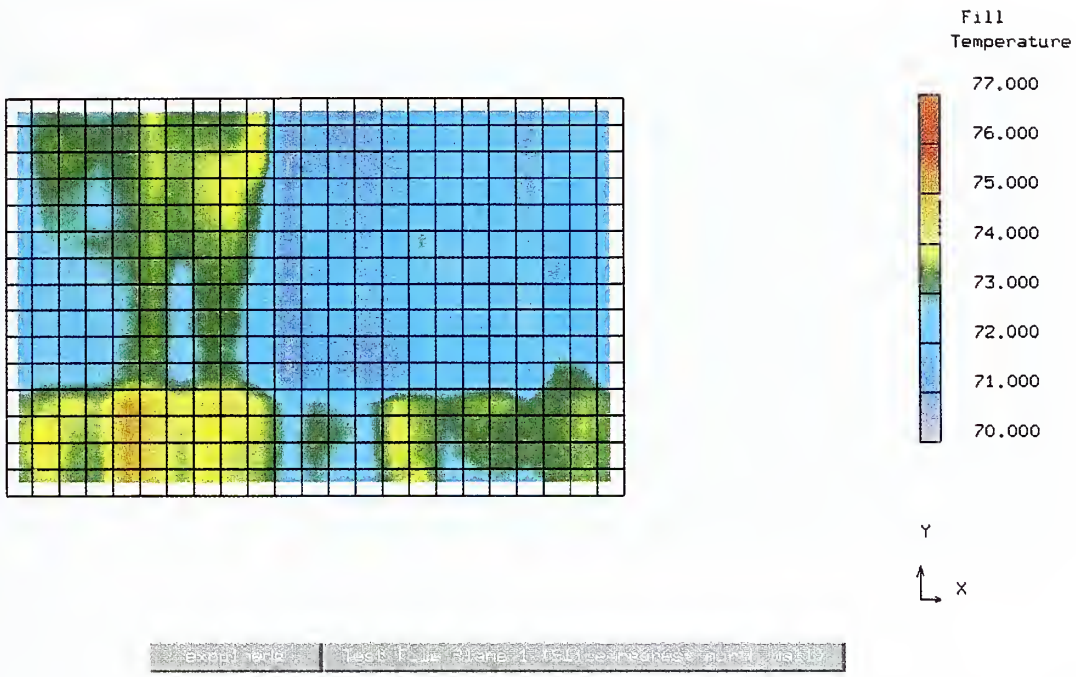


Figure 4.72 *Fill Plot of Temperature Field (Experimental) at Plane 1 (Plane 0.15m (6") from North Wall). Empty Room Case.*

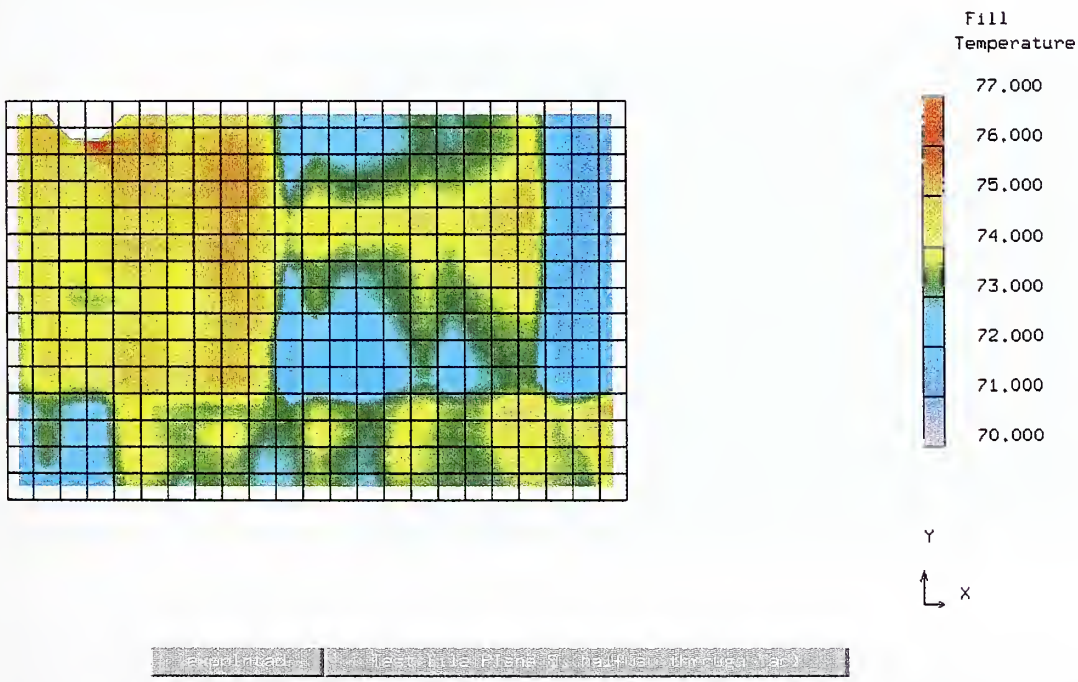


Figure 4.73 *Fill Plot of Temperature Field (Experimental) at Plane 8 (Plane 1.22m (48") from North Wall). Empty Room Case.*

Figure 4.74 *Fill Plot of Temperature Field (CFD) at Plane 1 (Plane 0.15m (6") from North Wall). Empty Room Case.*

Figure 4.75 *Fill Plot of Temperature Field (CFD) at Plane 8 (Plane 1.22m (48") from North Wall). Empty Room Case.*

4.2.3.2.2 Populated Room

For ease of comparison here, the experimental data are overlaid on top of the CFD results for this section of work. The experimental data are represented as contour lines, i.e., lines of the same value, while the CFD results are represented as fill plots.

Speed Results

The comparison between the experimental and CFD speed field results at 1.02m (40") from the south wall are shown in figure 4.76. Note that the left side of the plot represents the east wall of the room, and the key range is between 0 and 40 fpm (0.2 m/s). The plot shows that, qualitatively, the CFD simulation predicts the plumes of air resulting from the heaters in the individual cages. However, the experimental data show several spots of high speed in the rest of the plot that cannot readily be explained. Further, the experimental data demonstrate a peak value of 0.86m/s (172 fpm) well away from the cage plumes, and other measurement points where the speed value is above 0.60m/s (120 fpm), whereas the CFD prediction shows more modest peaks. Moving further towards the North Wall, figure 4.77 shows the comparison at the plane 1.93m (76") from the south wall. The experimental data again look a little uncertain. In particular, the high speeds in the lower right and left sides of the plot appear very similar to those in the previous plot. In this physical scenario, the room has very different boundary conditions near the north and south walls, and so these high spots appear unrealistic. Further, the peak experimental speed at this plane is 1.25m/s (250 fpm), with various other places showing values above 1.00m/s (200 fpm). Finally, the experimental data do not show any indication of the effect of the exhaust fan in the corner of the room. This feature is clearly evident in the CFD field.

Temperature Results

The comparisons between the experimental and CFD temperature field data at planes 0.71m, 1.02m, 1.32m, 1.63m, 1.93m and 2.13m (28", 40", 52", 64", 76, and 84") from the South Wall are shown in figures 4.78 to 4.83 respectively. Note that the left side of the plot represents the east wall of the room, and the key range is between 21.1 °C to 25.0 °C (70.0 and 77.0 °F). The planes represent comparisons close to the South Wall cage rack through to the North Wall door. The plots show that there is generally very good agreement between the experimental and CFD results at each of the planes. The CFD also correctly predicts many of the physical features exhibited by the experimental data, for example, the stratification of the air temperature shown most clearly in figure 4.82, and the diffuser airflow shown in figure 4.80.

The percentage differences between the experimental and CFD results confirm the good agreement between the two sets of data, as indicated in Tables 4.2.15 to 4.2.20. In particular, the average difference at the 0.71m (28") plane is 11.9 percent, at the 1.02m (40") plane is 13.0 percent, at the 1.32m (52") plane is 18.7 percent, at the 1.63m (64") plane is 11.9 percent, at the 1.93m (76") plane is 12.1 percent, and at the 2.13m (84") plane is 18.5 percent. These

differences again are within normal values of 20 percent commonly accepted as experimental uncertainty.

Table 4.2.15 Table of percent Difference between Experimental and CFD Temperature Data at Plane 0.71m (28") from South Wall

Dist. from Floor (")	Distance From West Wall (")												
	2	14	26	38	50	62	74	86	98	110	118	130	142
84	15.2	7.1	4.8	3.9	2.2	15.7	6.1	5.7	25.3	15.3	17.2	12.1	7.7
72	14.0	11.3	1.2	5.7	3.8	22.6	0.6	7.3	15.1	22.4	7.2	12.8	9.3
60			14.4	10.8	9.9	23.4	6.4	1.3	15.9	6.1	14.9		
48			22.0	4.4	1.0	19.2	1.1	0.5	2.2	13.4	17.8		
36			27.6	7.8	2.8	8.4	14.3	0.6	2.9	24.3	22.7		
24			22.2	1.0	12.7	6.9	1.0	13.9	27.9	23.6	5.6		
12			3.0	10.4	11.0	7.4	6.3	13.5	37.5	4.0	21.6		

Table 4.2.16 Table of percent Difference between Experimental and CFD Temperature Data at Plane 1.02m (40") from South Wall

Dist. from Floor (")	Distance From West Wall (")												
	2	14	26	38	50	62	74	86	98	110	118	130	142
84	7.6	13.5	6.1	0.6	2.9	13.6	39.9	26.4	17.3	7.3	6.7	3.8	31.8
72	10.3	25.6	19.1	3.0	0.9	12.4	13.1	16.2	0.5	2.7	5.6	1.5	26.6
60			34.0	6.8	2.5	7.3	8.1	5.8	10.0	1.3	23.7		
48			27.2	9.2	2.4	10.1	12.1	16.5	14.7	6.0	20.0		
36			34.0	12.9	4.9	2.3	17.0	13.1	15.9	7.1	29.9		
24			29.8	5.6	14.0	10.6	2.0	9.8	14.1	2.9	6.8		
12			11.9	14.5	9.6	12.3	6.7	12.4	21.4	7.0	9.2		

Table 4.2.17 Table of percent Difference between Experimental and CFD Temperature Data at Plane 1.32m (52") from South Wall

Dist. from Floor (")	Distance From West Wall (")												
	2	14	26	38	50	62	74	86	98	110	118	130	142
84	23.9	3.1	5.5	14.6	29.8	22.6	29.6	36.4	10.6	11.6	13.1	17.2	4.6
72	21.1	4.9	4.5	14.6	21.0	22.6	37.0	25.9	12.7	14.2	3.9	15.4	5.0
60			15.6	11.4	19.5	23.1	32.8	12.5	3.4	20.3	9.9		
48			7.9	21.8	24.1	18.1	34.5	15.6	6.1	33.7	1.2		
36			16.1	18.6	23.0	19.0	26.0	14.9	7.9	31.7	7.6		
24			3.6	11.3	25.3	29.9	25.3	23.3	33.5	21.4	17.1		
12			11.8	4.4	19.1	20.0	3.0	29.3	40.3	7.9	27.3		

Table 4.2.18 Table of percent Difference between Experimental and CFD Temperature Data at Plane 1.63m (64") from South Wall

Dist. from Floor (")	Distance From West Wall (")												
	2	14	26	38	50	62	74	86	98	110	118	130	142
84	0.9	22.5	8.8	2.7	0.3	13.1	7.7	4.7	12.1	11.9	15.1	5.1	7.6
72	6.4	30.6	2.7	11.8	2.2	13.0	11.5	14.2	6.1	2.5	14.2	13.5	5.6
60			28.1	7.3	3.6	7.5	13.0	15.5	1.3	4.8	35.8		
48			26.5	6.4	7.3	7.4	18.5	17.3	0.3	9.6	28.9		
36			33.1	14.4	5.3	7.9	15.1	8.1	4.4	1.9	41.4		
24			27.5	6.6	7.2	4.8	0.9	7.0	17.6	5.8	29.0		
12			7.8	13.9	2.1	0.4	10.9	4.5	15.3	13.2	6.4		

Table 4.2.19 Table of percent Difference between Experimental and CFD Temperature Data at Plane 1.93m (76") from South Wall

Dist. from Floor (")	Distance From West Wall (")												
	2	14	26	38	50	62	74	86	98	110	118	130	142
84	1.6	15.3	4.8	0.5	0.2	12.0	13.0	1.7	0.2	2.4	2.8	1.5	5.3
72	5.6	17.5	4.2	4.2	2.7	13.6	14.6	6.7	3.9	7.7	4.5	15.2	7.4
60			35.0	6.4	2.6	9.2	10.1	16.7	9.1	12.9	8.0		
48			30.0	11.6	1.8	10.3	11.1	13.6	17.4	16.8	14.2		
36			24.0	16.3	4.9	7.0	16.0	22.9	12.6	17.8	9.5		
24			21.7	5.3	18.6	11.1	7.2	14.5	41.3	25.1	13.2		
12			2.7	7.4	18.4	10.1	4.6	14.9	33.8	3.2	19.0		

Table 4.2.20 Table of percent Difference between Experimental and CFD Temperature Data at Plane 2.13m (84") from South Wall

Dist. from Floor (")	Distance From West Wall (")												
	2	14	26	38	50	62	74	86	98	110	118	130	142
84	1.4	2.3	5.8	9.7	14.0	8.3	25.3	13.2	17.4	17.3	13.6	9.2	10.0
72	3.9	18.1	4.5	9.3	12.5	8.9	27.4	16.6	28.6	29.6	22.4	14.9	6.9
60			22.3	9.2	12.0	10.2	28.3	24.2	20.4	29.7	26.7		
48			16.3	14.8	14.3	5.0	24.7	28.6	23.3	32.2	26.1		
36			25.6	19.9	16.5	9.5	24.1	22.0	23.8	33.2	23.8		
24			11.1	14.2	17.2	16.0	12.6	11.4	35.9	28.0	31.6		
12			6.1	1.8	15.4	9.5	10.8	21.7	35.5	9.9	32.5		

Concentration Results

The comparison between the experimental and CFD concentration (CO_2) results at the planes 0.71m, 1.02m, 1.32m, 1.63m, 1.93m, and 2.13m (28", 40", 52", 64", 76" and 84") from the south wall are shown in figures 4.84 to 4.89, respectively. Note that the left side of the plot represents the east wall, and that the key shows a range between 650 and 1200 ppm. The experimental concentration fields appear reasonable except for two large values close to the floor of the room, either side of the central plane: this feature is evident at all experimental planes considered, and is particularly noticeable in figure 4.86. There is no obvious physical reason for these two high spots of concentration, but the fact that they appear at every experimental plane indicates a systematic error at this vertical height. Other than these two locations, the comparison between the experimental and CFD data sets can be seen to be very good.

The percentage differences between the experimental and CFD results confirm the good agreement between the two sets of data, as indicated in Tables 4.2.21 to 4.2.26. In particular, the average difference at the 0.71m (28") plane is 14.9 percent, at the 1.02m (40") plane is 15.2 percent, at the 1.32m (52") plane is 15.2 percent, at the 1.63m (64") plane is 14.2 percent, at the 1.93m (76") plane is 13.7 percent, and at the 2.13 (84") plane is 13.8 percent. It should be noted that these averages would be lower with the elimination of the concentration hot spots.

Table 4.2.21 Table of percent Difference between Experimental and CFD Concentration Data at Plane 0.71m (28") from South Wall

Dist. from Floor (")	Distance From West Wall (")												
	2	14	26	38	50	62	74	86	98	110	118	130	142
84	11.0	2.8	15.7	24.5	11.4	5.9	16.3	14.0	10.5	11.3	12.1	23.3	0.9
72	10.9	5.1	10.3	26.1	14.3	4.9	21.0	20.8	14.1	15.3	9.3	22.4	4.4
60			3.8	23.7	5.5	6.3	18.4	16.8	18.8	15.8	1.8		
48			7.5	24.4	10.3	2.5	19.7	14.8	11.4	17.4	2.3		
36			0.3	29.0	12.6	5.2	16.0	16.9	10.9	18.9	5.1		
24			7.3	16.1	27.9	21.6	11.3	1.7	35.4	17.5	6.1		
12			11.4	22.8	33.2	21.6	11.3	14.7	33.4	15.9	17.1		

Table 4.2.22 Table of percent Difference between Experimental and CFD Concentration Data at Plane 1.02m (40") from South Wall

Dist. from Floor (")	Distance From West Wall (")												
	2	14	26	38	50	62	74	86	98	110	118	130	142
84	11.1	0.5	11.8	23.0	16.8	27.3	35.1	27.2	15.1	9.7	8.7	19.7	3.5
72	6.3	1.3	4.6	23.8	15.3	12.5	23.0	22.7	9.4	14.1	6.4	19.6	2.5
60			7.2	24.6	7.2	7.5	22.6	18.0	5.2	11.6	5.5		
48			8.4	25.1	13.0	3.7	22.5	20.5	1.6	10.8	2.8		
36			9.2	25.1	15.4	10.2	18.3	20.8	4.3	13.1	0.6		
24			2.6	17.1	29.7	22.2	14.5	14.8	29.3	14.8	5.1		
12			12.6	12.9	30.1	22.2	12.0	12.7	30.1	13.1	14.8		

Table 4.2.23 Table of percent Difference between Experimental and CFD Concentration Data at Plane 1.32m (52") from South Wall

Dist. from Floor (")	Distance From West Wall (")												
	2	14	26	38	50	62	74	86	98	110	118	130	142
84	10.0	5.9	6.7	20.7	27.7	23.5	36.3	38.6	13.6	6.5	7.0	17.1	1.3
72	10.3	20.8	8.6	18.7	12.6	2.6	27.5	17.1	3.2	7.1	1.4	18.0	1.6
60			7.3	21.7	10.0	3.1	28.2	12.9	1.5	9.8	8.6		
48			4.8	22.4	18.1	10.0	24.8	17.6	2.7	12.4	8.6		
36			5.5	23.0	15.1	16.9	22.1	21.6	1.1	12.8	12.0		
24			1.9	16.8	23.8	20.3	18.3	16.4	27.8	11.7	8.6		
12			9.7	12.7	27.8	19.5	11.9	10.0	32.4	10.3	18.0		

Table 4.2.24 Table of percent Difference between Experimental and CFD Concentration Data at Plane 1.63m (64") from South Wall

Dist. from Floor (")	Distance From West Wall (")												
	2	14	26	38	50	62	74	86	98	110	118	130	142
84	12.6	0.1	7.3	22.5	6.7	1.5	13.5	17.5	7.4	8.1	5.3	15.4	12.2
72	5.4	9.6	8.7	19.8	3.1	2.7	17.8	25.4	11.4	6.2	5.1	12.4	10.7
60			7.0	23.1	3.9	2.4	17.3	30.3	17.3	9.5	0.1		
48			7.1	24.1	12.9	5.9	19.4	26.9	16.7	12.8	9.9		
36			1.3	21.6	12.5	9.2	16.6	26.5	11.3	13.2	16.0		
24			1.4	16.1	21.4	16.8	15.4	20.0	29.3	17.8	10.2		
12			10.3	22.8	25.1	18.5	7.9	13.4	30.9	10.3	18.5		

Table 4.2.25 Table of percent Difference between Experimental and CFD Concentration Data at Plane 1.93m (76") from South Wall

Dist. from Floor (")	Distance From West Wall (")												
	2	14	26	38	50	62	74	86	98	110	118	130	142
84	8.6	11.2	13.4	22.3	4.2	2.3	9.4	7.9	10.1	5.7	8.0	17.7	4.2
72	2.4	3.8	21.0	19.6	8.0	2.9	20.8	12.4	14.2	6.4	9.5	12.6	1.7
60			10.7	22.0	11.4	8.5	16.2	17.6	11.7	8.3	26.9		
48			10.3	22.7	9.8	3.3	13.6	18.3	13.1	12.3	11.4		
36			4.6	23.4	10.7	7.5	14.3	22.3	9.7	13.1	9.5		
24			4.5	16.3	20.9	16.0	14.1	17.8	26.2	17.5	20.3		
12			11.1	12.7	23.1	18.5	4.1	12.7	30.3	13.0	18.5		

Table 4.2.26 Table of percent Difference between Experimental and CFD Concentration Data at Plane 2.13m (84") from South Wall

Dist. from Floor (")	Distance From West Wall (")												
	2	14	26	38	50	62	74	86	98	110	118	130	142
84	6.8	7.8	25.2	24.9	3.0	3.2	11.4	6.1	8.0	3.9	2.7	13.6	8.0
72	0.3	7.0	18.7	28.9	6.5	7.1	13.6	6.3	10.6	6.1	10.4	11.4	2.0
60			6.9	24.5	9.5	4.0	11.8	14.4	14.5	7.5	3.4		
48			18.8	17.0	8.0	1.9	12.2	15.5	5.1	8.9	10.7		
36			26.4	22.7	6.8	9.9	13.5	16.3	2.5	12.1	9.8		
24			35.2	27.2	20.8	16.0	17.7	15.7	26.5	17.0	20.3		
12			37.3	12.7	23.2	16.0	4.0	11.9	29.6	6.1	20.9		

Discussion and Conclusions

From the above results it can be seen that the CFD simulation for the populated room agrees well with the experimental data for both the temperature and concentration (CO_2) data, but the speed field displays features that cannot be readily explained. This conclusion mirrors that from the empty room validation exercise. The conclusion is that the measured speed data are again the problem, because the comparison for the temperature and concentration data would also be erroneous if the CFD simulation is predicting the physical flow features in the room incorrectly (other than for very localized effects not included in the model). The above data again demonstrate the inherent difficulty in measuring low speed data accurately in a test facility.

Further, especially in the case of the temperature and concentration comparisons, although the experimental data can be used to obtain some feel for the conditions within the room, the CFD results provide a more complete picture of the flow field distributions and physical processes present.

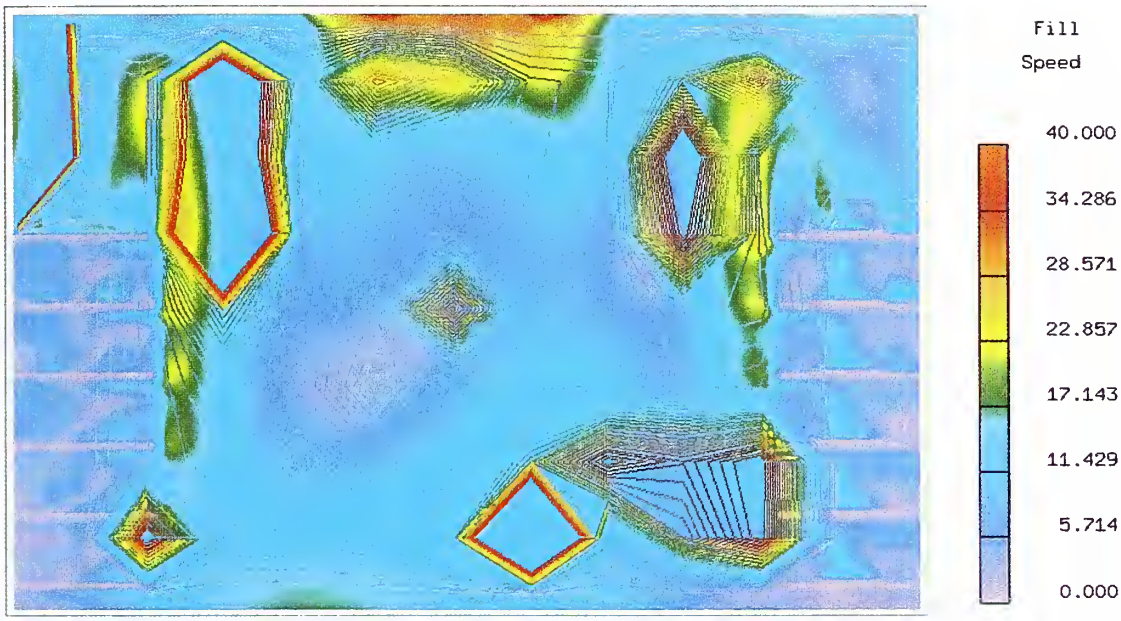


Figure 4.76 *Comparison of Experimental and CFD Speed Fields at 1.02m (40") from South Wall.*

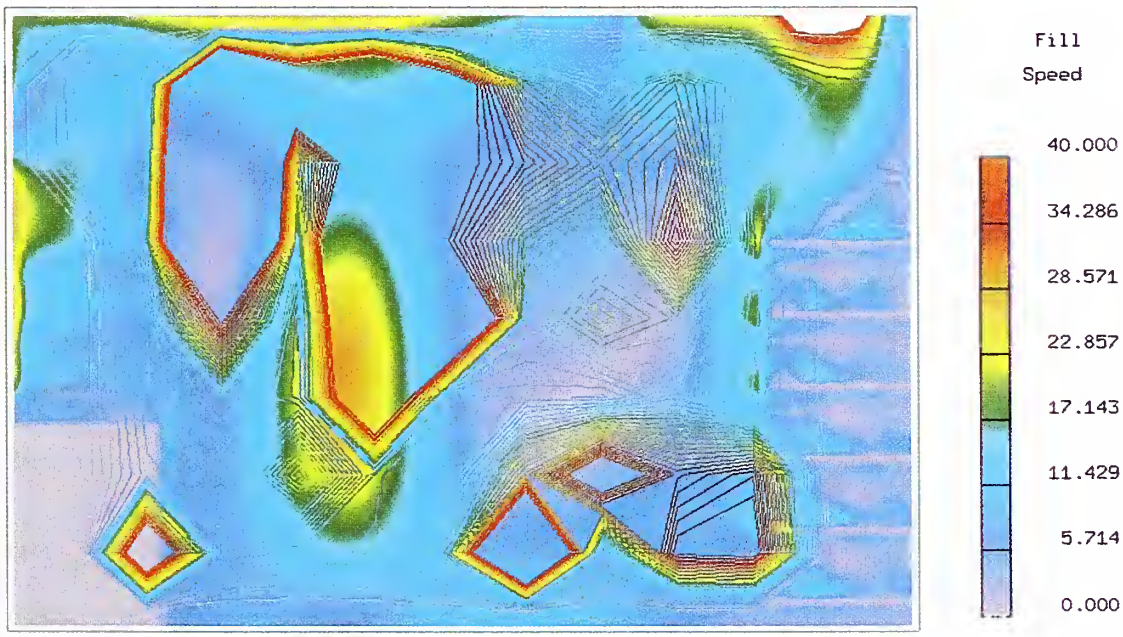


Figure 4.77 *Comparison of Experimental and CFD Speed Fields at 1.93m (76") from South Wall.*

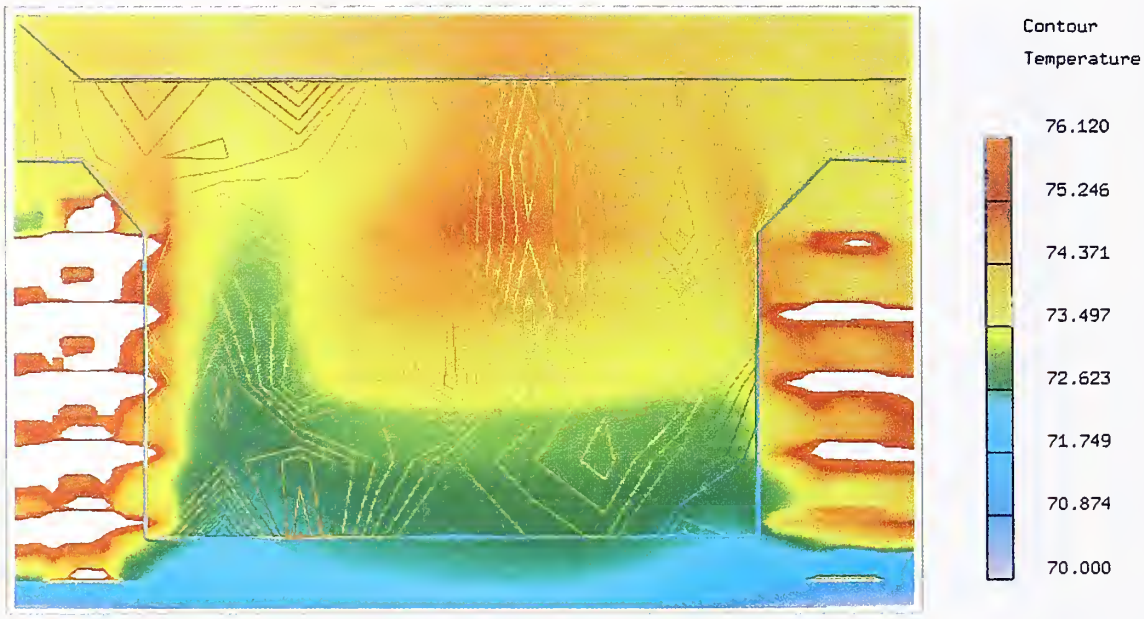


Figure 4.78 *Comparison of Experimental and CFD Temperature Fields at 0.71m (28") from South Wall.*

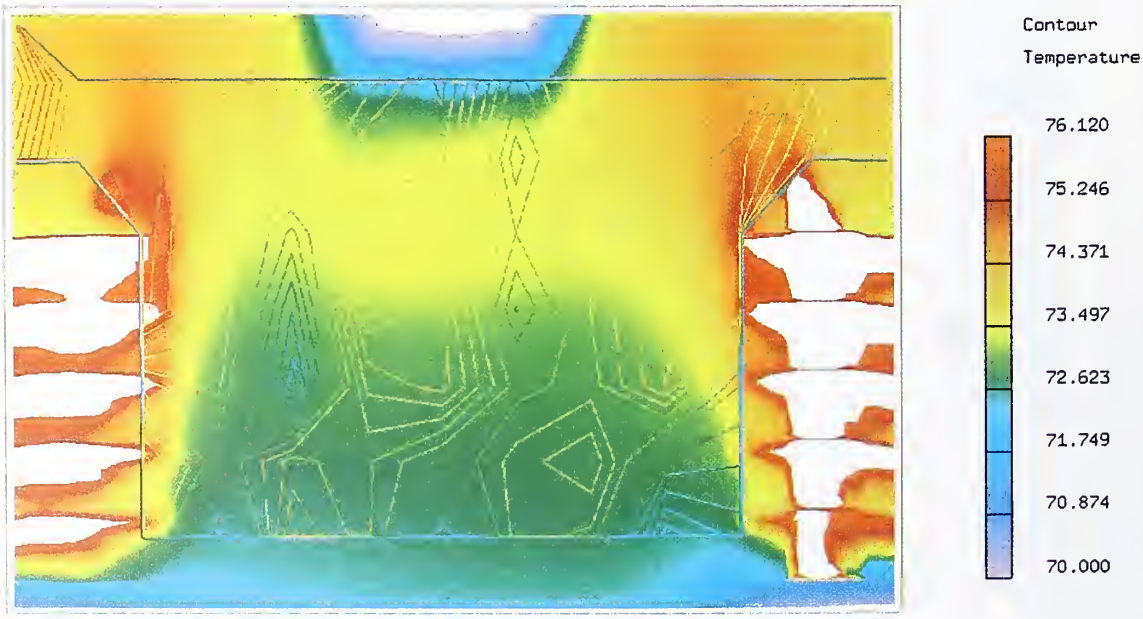


Figure 4.79 *Comparison of Experimental and CFD Temperature Fields at 1.02m (40") from South Wall.*

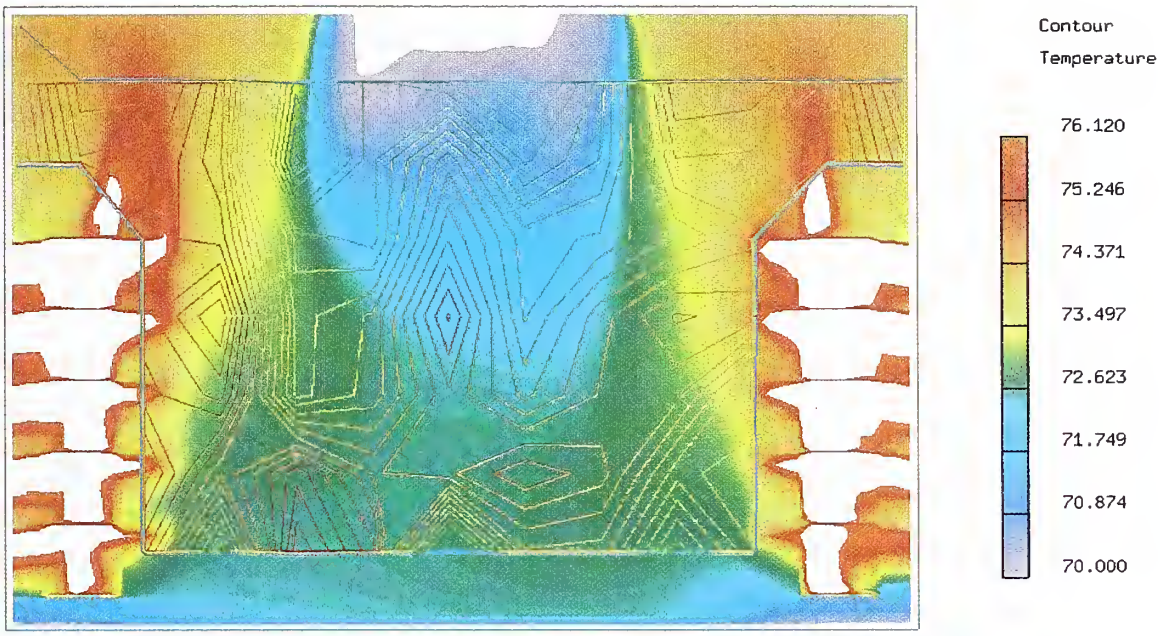


Figure 4.80 *Comparison of Experimental and CFD Temperature Fields at 1.32m (52") from South Wall.*

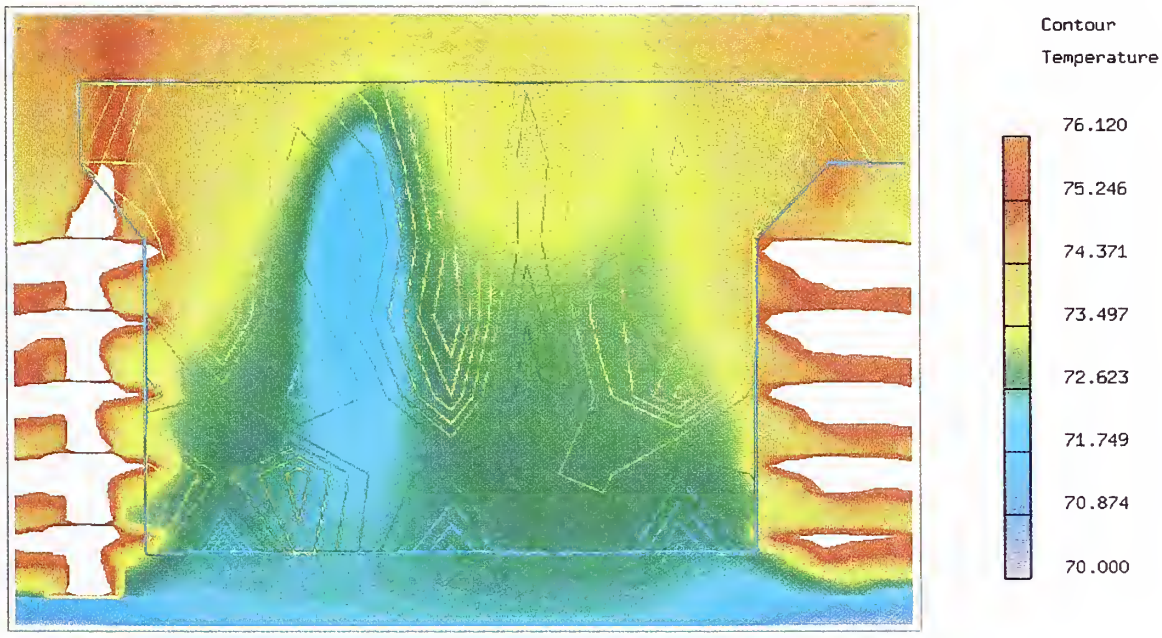


Figure 4.81 *Comparison of Experimental and CFD Temperature Fields at 1.63m (64") from South Wall.*

Figure 4.82 *Comparison of Experimental and CFD Temperature Fields at 1.93m (76") from South Wall.*

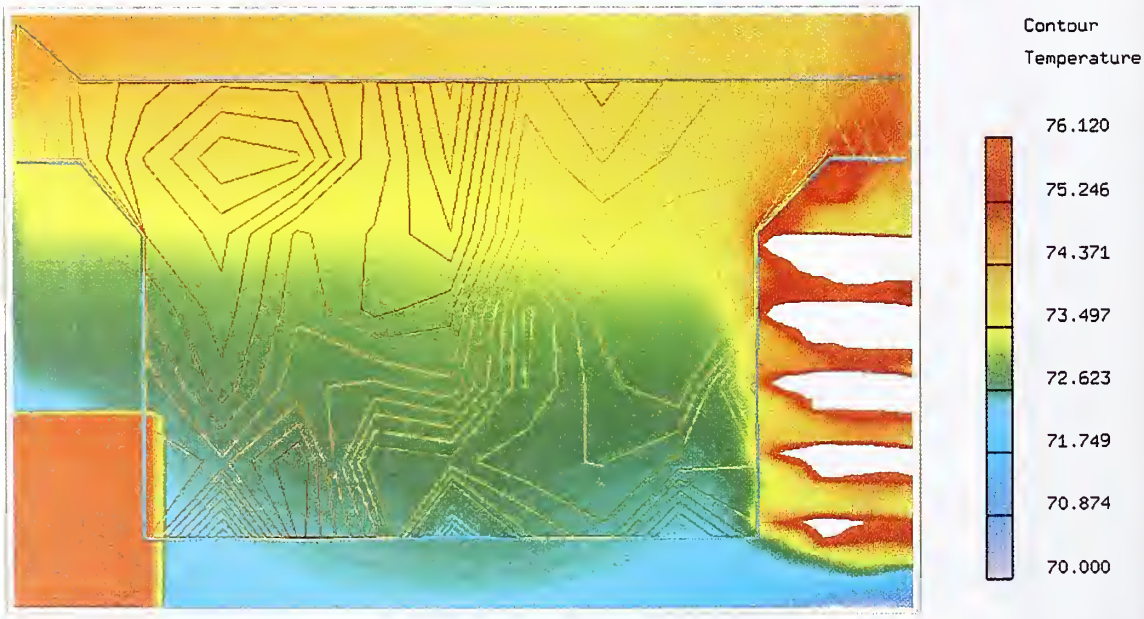


Figure 4.83 *Comparison of Experimental and CFD Temperature Fields at 2.13m (84") from South Wall.*

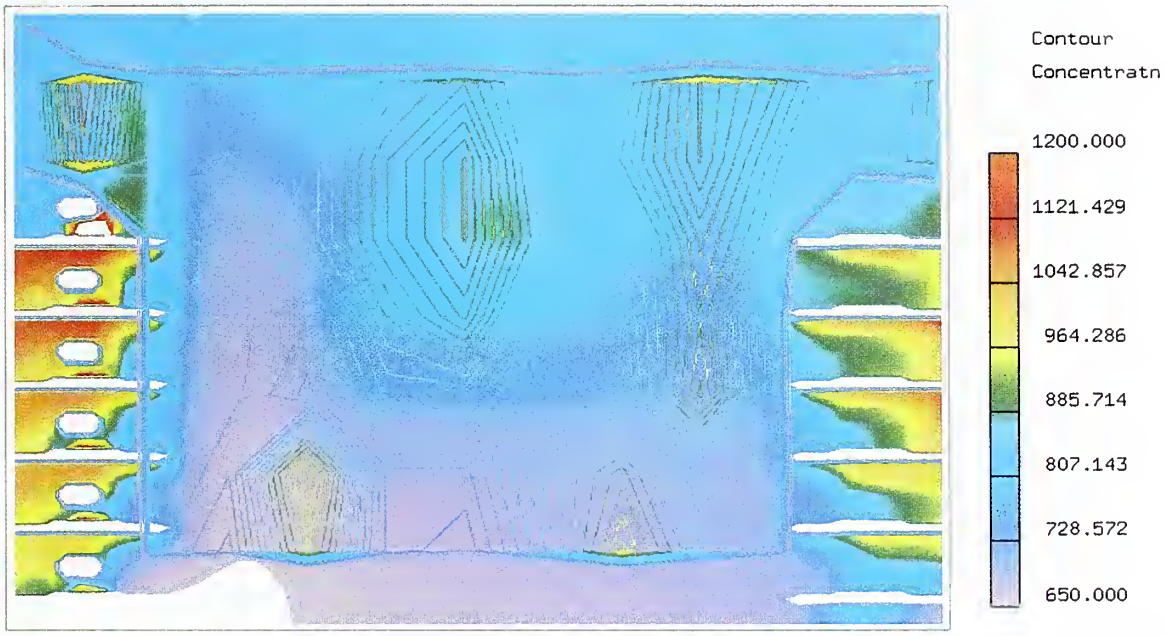


Figure 4.84 *Comparison of Experimental and CFD Concentration Fields at 0.71m (28") from South Wall.*

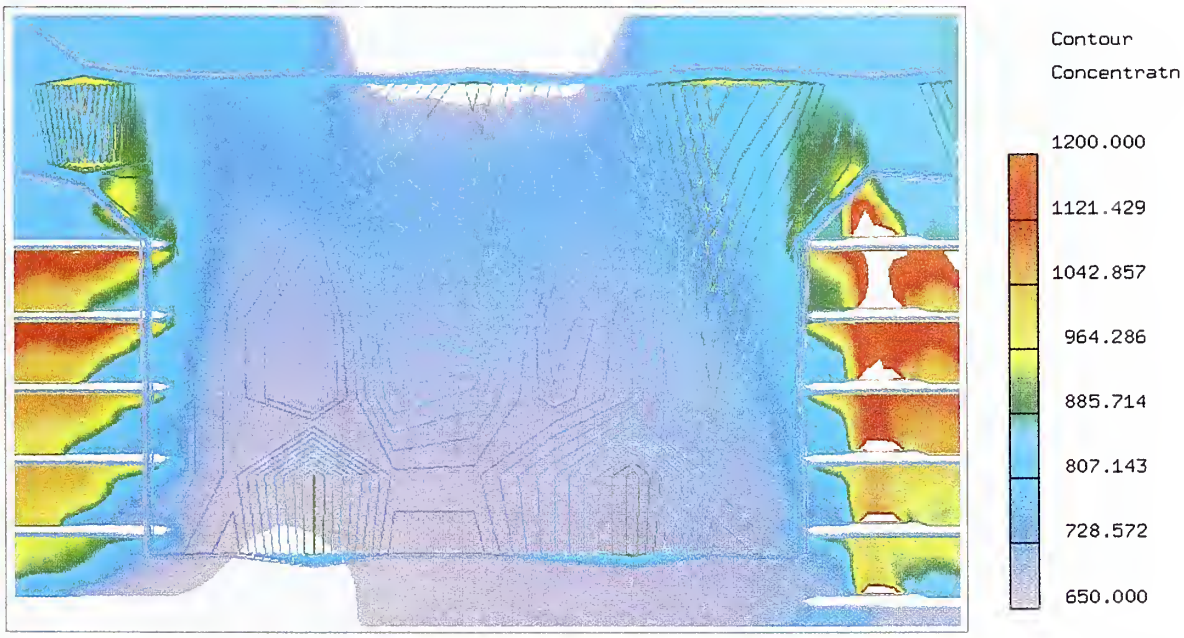


Figure 4.84 *Comparison of Experimental and CFD Concentration Fields at 1.02m (40") from South Wall.*

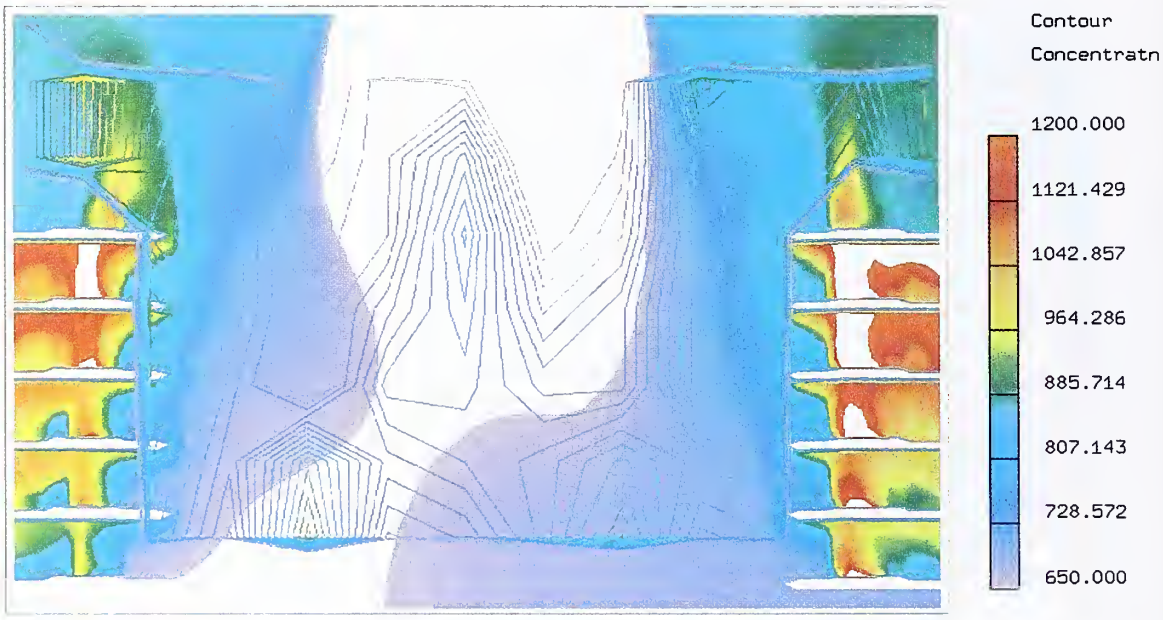


Figure 4.85 *Comparison of Experimental and CFD Concentration Fields at 1.32m (52") from South Wall.*

Figure 4.86 *Comparison of Experimental and CFD Concentration Fields at 1.63m (64") from South Wall.*

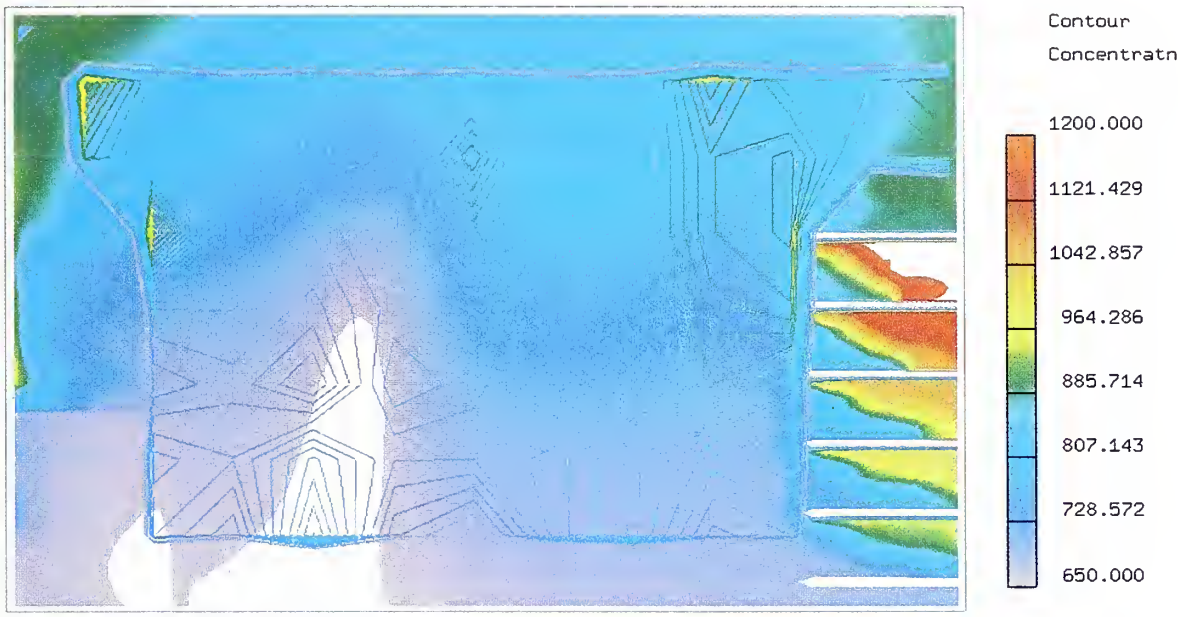


Figure 4.87 *Comparison of Experimental and CFD Concentration Fields at 1.93m (76") from South Wall.*

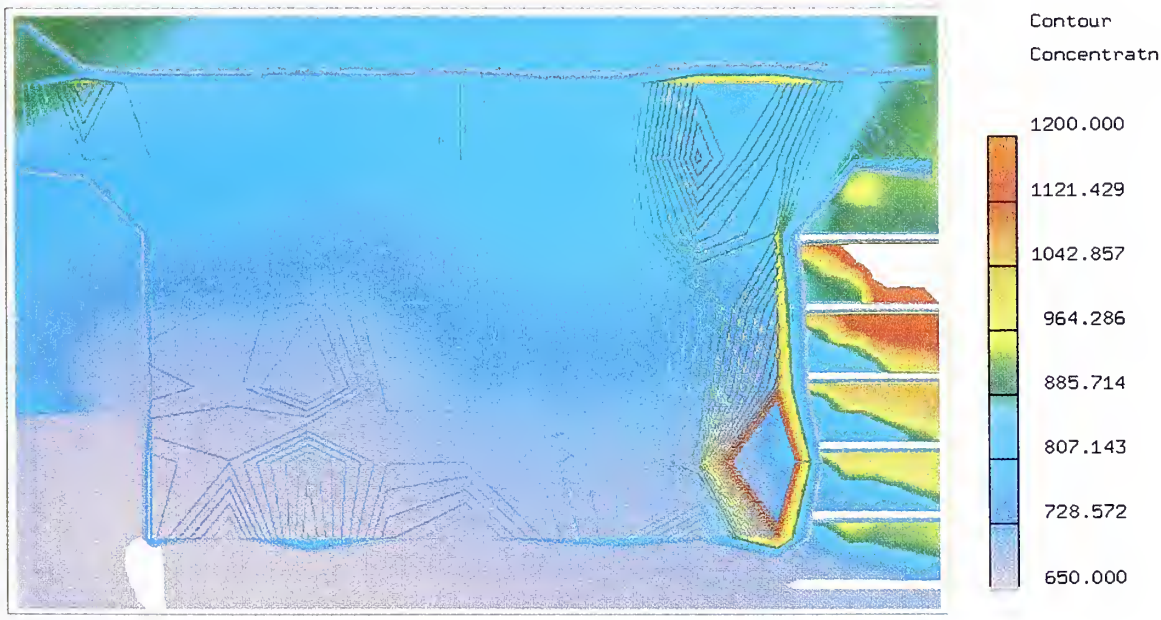


Figure 4.88 *Comparison of Experimental and CFD Concentration Fields at 2.13m (84") from South Wall.*

SECTION V

CFD METHODOLOGY

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5. CFD METHODOLOGY

Airflow and heat transfer within a fluid are governed by the principles of conservation of mass, momentum, and thermal energy. In order to predict the airflow and temperature, as well as the distribution of contaminants at any given point in the animal room space, CFD techniques are used to represent the fundamental laws of physics describing fluid flow and heat transfer.

5.1 Methodology Overview

This section outlines the fundamental aspects of CFD, the equations utilized, and the methodology adopted with respect to the problem at hand.

5.1.1 What is CFD?

Computational fluid dynamics can be summarized by the following definitions:

Computational

The computational part of CFD means using computers to solve problems in fluid dynamics. This can be compared to the other main areas of fluid dynamics, such as theoretical and experimental.

Fluid

When most people hear the term fluid they think of a liquid such as water. In technical fields, fluid actually means anything that is not a solid, so that both air and water are fluids. More precisely, any substance that cannot remain at rest under a sliding or shearing stress is regarded as a fluid.

Dynamics

Dynamics is the study of objects in motion and the forces involved. The field of fluid mechanics is similar to fluid dynamics, but usually is considered to be the motion through a fluid of constant density.

CFD is the science of computing the motion of air, water, or any other gas or liquid.

5.1.2 Overview of CFD

The science of computational fluid dynamics is made up of many different disciplines from the fields of aeronautics, mathematics, and computer science. A scientist or engineer working in the CFD field is likely to be concerned with topics such as stability analysis, graphic design, and aerodynamic optimization. CFD may be structured into two parts: generating or creating a solution, and analyzing or visualizing the solution. Often the two parts overlap, and a solution is analyzed while it is in the process of being generated in order to ensure no mistakes have been made. This is often referred to as validating a CFD simulation.

5.1.3 CFD Solutions

When scientists or engineers try to solve problems using computational fluid dynamics, they usually have a specific outcome in mind. For instance, an engineer might want to find out the amount of lift a particular airfoil generates. In order to determine this lift, the engineer must create a CFD solution, or a simulation, for the space surrounding the airfoil. At every point in space around the airfoil, called the grid points, enough information must be known about the state of a fluid particle to determine exactly what direction it would travel and with what velocity. This information is called flow variables.

5.1.4 Governing Equations of Fluid Dynamics

The governing equations of fluid dynamics represent the conservation of mass, momentum, and energy for a fluid continuum. The conservation of mass states that mass cannot be created or destroyed, and the conservation of energy is similar. The conservation of momentum is simply Newton's Law of Motion (force = mass x acceleration) that is cast in a form suitable for fluid dynamics. Because the governing equations are the three conservation laws, they are also referred to as the conservation law equations. The governing equations receive their name because they determine the motion of a fluid particle under certain boundary conditions.

The governing equations remain the same, however, the boundary conditions will change for each problem. For example, the shape of the object may be different, or the speed of the undisturbed air may change. These changes would be implemented through a different set of boundary conditions. In general, a boundary condition defines the physical problem at specific positions. Fundamental boundary conditions include the no-slip condition at the interface between solid and fluid that leads to the formation of a wall boundary layer. Another is the fixed mass outlet where it is ensured that a constant mass flow is extracted from the solution domain at a specified plane.

The governing equations have actually been known for over 150 years. In the 19th century, two scientists, Navier and Stokes, described the equations for a viscous, compressible fluid, which are now known as the Navier-Stokes equations. These equations form a set of differential equations. The generic form of these relationships follow the advection diffusion equation, 5.1:

$$\frac{\partial}{\partial t}(\rho\varphi) + div(\rho\nabla\varphi - \Gamma_\varphi grad\varphi) = S_\varphi \tag{5.1}$$

transient + advection - diffusion = source

The variable phi (φ) represents any of the predicted quantities such as air velocity, temperature, or concentration at any point in the three-dimensional model. All subsequent terms are identified in section 5.6. This equation is derived by considering a small, or finite, volume of fluid. The left- hand side of the equation refers to the change in time of a variable within this volume added to that advected into it, minus the amount diffused out. This is in turn equal to the amount of the variable flux (i.e., momentum, mass, thermal energy) that is added or subtracted within the finite volume. Though deceptively simple, only the emergence of ever faster computers over the past two decades has made it possible to solve the real world problems governed by this equation.

Despite their relatively old age, the Navier-Stokes equations have never been solved analytically. The numerical techniques used to solve these coupled mathematical equations are commonly known as computational fluid dynamics, or CFD. At the present time, CFD is the only means of generating complete solutions.

The Navier-Stokes equations are a set of partial differential equations that represent the equations of motion governing a fluid continuum. The set contains five equations, mass conservation, three components of momentum conservation, and energy conservation. In addition, certain properties of the fluid being modeled, such as the equation of state, must be specified. The equations themselves can be classified as nonlinear, and coupled. Nonlinear, for practical purposes, means that solutions to the equations cannot be added together to get solutions to a different problem (i.e., solutions cannot be superimposed). Coupled means that each equation in the set of five depends upon the others; they must all be solved simultaneously. If the fluid can be treated as incompressible and nonbuoyant, then the conservation of energy equation can be decoupled from the others and a set of only four equations must be solved simultaneously, with the energy equation being solved separately, if required.

The majority of fluid dynamics flows are modeled by the Navier-Stokes equations. The Navier-Stokes equations also describe the behavior of turbulent flows. The many scales of motion that turbulence contains, especially its microscales, cause the modeling of turbulent processes to require an extremely large number of grid points. These simulations are performed today, and fall into the realm of what is termed direct numerical simulations (DNS). The DNS are currently only able to model a very small region, in the range of one cubic foot, using supercomputers. Differential equations represent differences, or changes, of quantities. The changes can be with respect to time or spatial locations. For example, in Newton's Law of

Motion (F = ma), the time rate of change of velocity, or acceleration, is equal to the force/unit mass. If the quantities depend on both time and space, the equations are written to take this into account and they are known as partial differential equations, or PDE's. In most general formulations, the governing equations for physical phenomena are written in terms of rates of change with respect to time and space, or as partial differential equations.

5.1.5 Flow Variables

The flow variables contain information about the fluid state at a point in space. Enough information must be maintained in order to specify a valid fluid state; i.e., two thermodynamic variables, such as pressure and temperature, and one kinematic variable, such as velocity. A velocity will usually have more than one component, i.e., in three dimensions it will have three components.

In this research, the variables under consideration are the three components of velocity, pressure, temperature, concentration, and two variables characterizing turbulent levels: turbulent kinetic energy and its rate of dissipation.

Over the past 25 years, CFD techniques have been used extensively and successfully in the mainly high-end sectors, such as the nuclear and the aerospace industries. In its raw and general form, CFD has always been the forte of fluids experts. The recent concept of tailoring CFD software, combined with the expertise in heating and ventilation in buildings, has made it possible to apply these powerful methods to provide fast and accurate results to designers under severe time and budgetary constraints. In fact, this project would not have been practical without these new elements in place.

5.1.6 How Does it Work?

In order to generate a CFD solution, two processes must be accomplished, namely;

- geometry definition and grid generation
- numerical simulation

In broad terms, grid generation is the act of specifying the physical configuration to be simulated and dividing it up into a three-dimensional grid containing a sufficient number of small regions known as control volume cells so that the Navier-Stokes partial differential equations can be solved iteratively. Numerical simulation is the process of applying a mathematical model to that configuration and then computing a solution. These two stages are sequential. The grid generation is performed before any numerical simulation work can be done.

5.1.6.1 Grid generation

Grid generation is the process of specifying the position of all of the control volume cells that will define both the simulation's physical configuration and the space surrounding it. Grid generation is one of the more challenging and time-consuming aspects of CFD because it involves creating a description of the entire configuration that the computer can understand. The model thus defined must include the relationship with the space surrounding the chosen model as well as the surfaces and processes contained within it. In both cases the most important factor is to maintain a suitable number of control volume cells in areas where there will be large or rapid changes occurring. These changes may be changes in geometry, such as a sharp corner of an object, or they may be sharp changes occurring in the flow field around the object, such as the edge of jet issuing from the diffuser. This is called maintaining a suitable grid resolution. Without a suitable grid resolution, valuable information can be lost in the numerical simulation process and the resulting solution can be misleading. Determining what exactly constitutes enough grid resolution is one of the most important jobs a CFD scientist or engineer performs. While too few control volume cells can lead to useless simulations, too many control volume cells can lead to computer requirements that cannot be fulfilled. A perfect example of this situation is trying to run the latest version of Microsoft Word on a 286 chip.

5.1.6.2 Numerical simulation

As with every other aspect of CFD, the numerical simulation process can also be broken into two steps, as follows:

1) <u>Modeling the Physics</u>

If the user does nothing else, then the boundary surfaces of the solution domain are "zero flow" (i.e., symmetry surfaces). These have zero mass flow, zero surface friction, and zero heat transfer. The interior of the domain contains only fluid as defined by properties such as density, viscosity, and so on. Anything else, such as inflow or outflow, walls, internal objects, or heat gains or losses must be specified explicitly by the user. These are known as boundary conditions.

The locations of boundary conditions are defined in terms of six spatial coordinates (xS, xE, yS, yE, zS, zE), in meters, referenced from the origin located on one corner of the solution domain. In the case of a two-dimensional planar (flat) boundary condition (the shelves) the orientation is specified and the six coordinates degenerate to five. Additionally, some planar boundary conditions should only affect the fluid (e.g., an external boundary wall has only one surface present in the solution domain).

For accurate geometrical representations, the grid lines (surfaces of the control volume cells) can be forced to align with a boundary condition. If this is not done then the boundary condition will

"snap" to the nearest grid line in the final model. This type of allowance is often acceptable when setting up room geometries. The exact location of an item need not be clearly defined.

Below is a list, with brief descriptions, of the boundary conditions relevant to the approach taken in this study, referred to in the sections of this report.

Rectangular Obstructions	Rectangular obstructions are three-dimensional, solid, rectangular objects, with faces aligned with x, y and z. Friction at all surfaces exposed to fluid is included. There are a number of possible thermal specifications: • Fixed uniform heat flux at all surfaces • Fixed uniform surface temperature • Solve in solid (to investigate conduction through solid)
External Walls	External walls are walls at the edges of the solution domain, or exceptionally internal walls for which solution is required only on one side and "external" conditions can be applied on the other side. Surface friction is evaluated automatically and there are a number of thermal options: • Prescribed heat flux • Prescribed inner wall surface temperature • Prescribed external temperature with detail of the heat transfer through the wall
Exhausts	Exhausts represent any outflow of air, usually when driven using mechanical means. The flow rate is specified as: • Fixed mass flow rate (kg/s) • Linear pressure drop/flow rate fan characteristic • External static pressure
Openings	Openings are any opening through which fluid can enter or leave the domain as a result of pressure differences. The temperature and angle of flow of incoming air can be specified. It is also possible to represent, for example, a grille across the opening by setting a pressure drop (see **Resistances**).

Resistances	Resistances cover any kind of flow resistance (i.e., pressure drops) caused by porous items within the flow domain. Two options are available: **Planar resistances:** These provide for areas where the resistance is thin and can be applied in one plane. The pressure drop is given by the expression: $DP = f \, ½ \rho (v/b)^2$ Where DP Pressure drop f loss coefficient ρ density v velocity of fluid b geometrical free area ratio of obstruction **Volume resistances:** These provide for areas where the resistance occupies a significant thickness in the solution domain and resistance will occur in more than one direction. The pressure drop is the same as for a planar resistance, except that it is expressed as pressure drop per meter and the factor and free area ratio is required for each coordinate direction. **Loss Coefficient and Free Area Ratio:** The loss coefficient will depend on the actual geometry of the item causing the pressure drop. This will be obtained from experiment or empirical relationships in textbooks. Care is needed as it may be set with respect to an approach velocity or device velocity. If the latter is chosen there will be an associated free area ratio so the program can correctly calculate the pressure drop. The free area ratio is not required if the setting is based on the approach velocity.

Sources	Planar and volume sources provide regions of defined source of heat or momentum, or fixed values of velocities, concentration, and/or temperature. The following options are available: • Prescribed source of heat, concentration, and/or momentum • Fixed values of velocity, concentration, and/or temperature • Linear source of heat, concentration, and/or momentum given by the expression: *source = coefficient (value – velocity or temperature)* The last option also allows the specification of a pressure drop that varies linearly with (velocity), rather than $(\text{velocity})^2$, which is defined through planar resistances. A pressure drop term is seen as a source term in the conservation of momentum equation (equation 5.3). A linear source of momentum can be arranged to replicate this term, as follows: • Source = coefficient(value – velocity) Considering the x-coordinate direction and setting value = 0, we obtain: • $\text{Source}_x = -\text{coefficient}_x \times \text{velocity}_x$ Which can be seen to be equivalent to: • $DP = -f_x \times \text{velocity}_x$
Supplies	Supplies are to bring air in from outside, normally, conditioned air from the main plant. The flow is set using: • Fixed mass flow rate (kg/s) • Linear pressure drop/flow rate fan characteristic The temperature and angle of flow of incoming air can be specified.
Thin Walls	Internal thin walls are thin solid surfaces within the solution domain that are aligned with the grid. Solution is carried out on both sides. The walls are impervious to flow but it is possible to specify heat transfer across them. Surface friction (different on each side if required) is evaluated.
Triangular Prisms	Triangular prisms are solid objects with a triangular cross section, and with all faces except the sloping face aligned with x, y, and z. All surfaces are zero friction and only the sloping surface has heat transfer. This is specified in terms of a temperature and heat transfer coefficient, or, as a fixed heat flux.

2) Numerically Solving the Physical Model

Integration is one of the cornerstones of calculus, the other being differentiation. In order to find the solution domain (the area under a solution curve) numerically, the curve would be chopped up into little pieces, and then the area under each little curve would be approximated. The sum of all of the approximate little areas would be close to the actual area under the curve. The difference between the actual and approximate areas is the numerical error. The object is to make this error so small it is not noticeable. In CFD, rather than integrating a relatively simple function like the equation for a curve, the governing equations of motion for a fluid continuum are integrated.

Let us consider a typical animal facility. The objective is to predict airflow, temperature, and concentration of any airborne contaminant at any point in the room space.

Figure 5.01 shows a set of design parameters such as

- *the geometry and layout of the animal room*
- *the sources of heat and contaminants,*
- *as well as the position of exhaust and ventilation systems.*

In order to do this, *the three-dimensional space* of the animal room is subdivided into a large number of *control volume cells* (figure 5.02). The size of the cells influences the detail and accuracy of the final results. In all the whole animal room cases, the number of grid cells ran into the hundreds of thousands, and, in some instances, totaled over one million grid cells.

The equations in each cell represent the mathematical definition of the equipment and phenomena contained within it. For example, a cell could encompass a volume that envelops the following:

- *a representation of a group of mice*
- *or some heat source*
- *or just some air.*

The CFD software will then attempt to solve the Navier-Stokes equation for a predetermined set of variables for each cell. In a typical three-dimensional calculation these variables would represent the following:

- *velocities in three directions,*
- *temperature,*
- *pressure,*
- *concentration,*
- *and the turbulence quantities.*

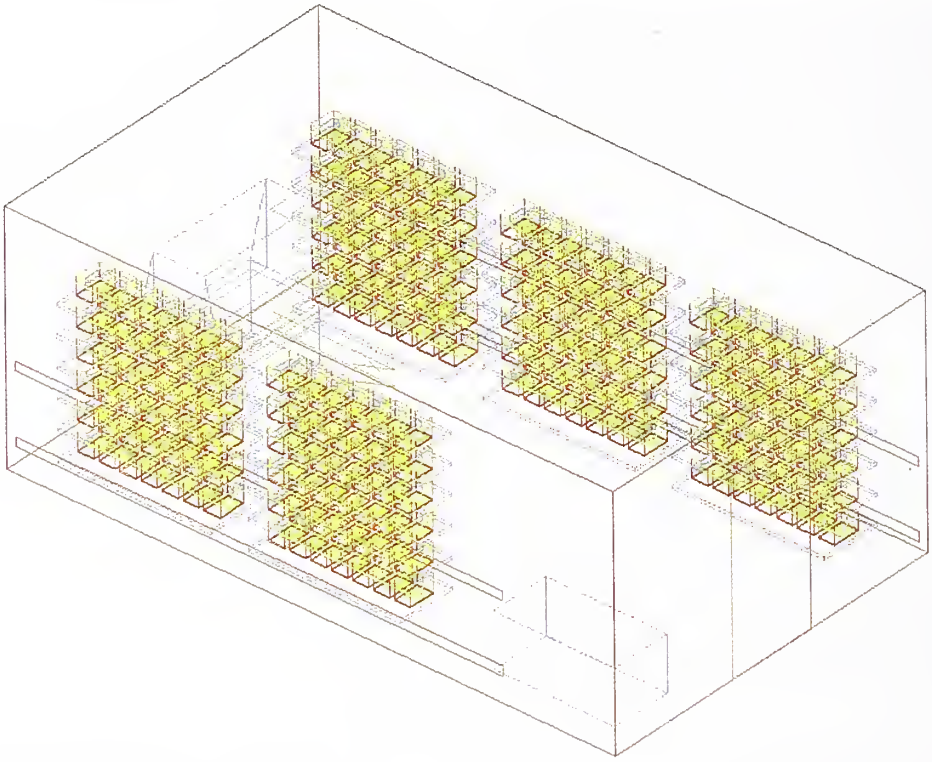

Figure 5.01 *Geometric Model*

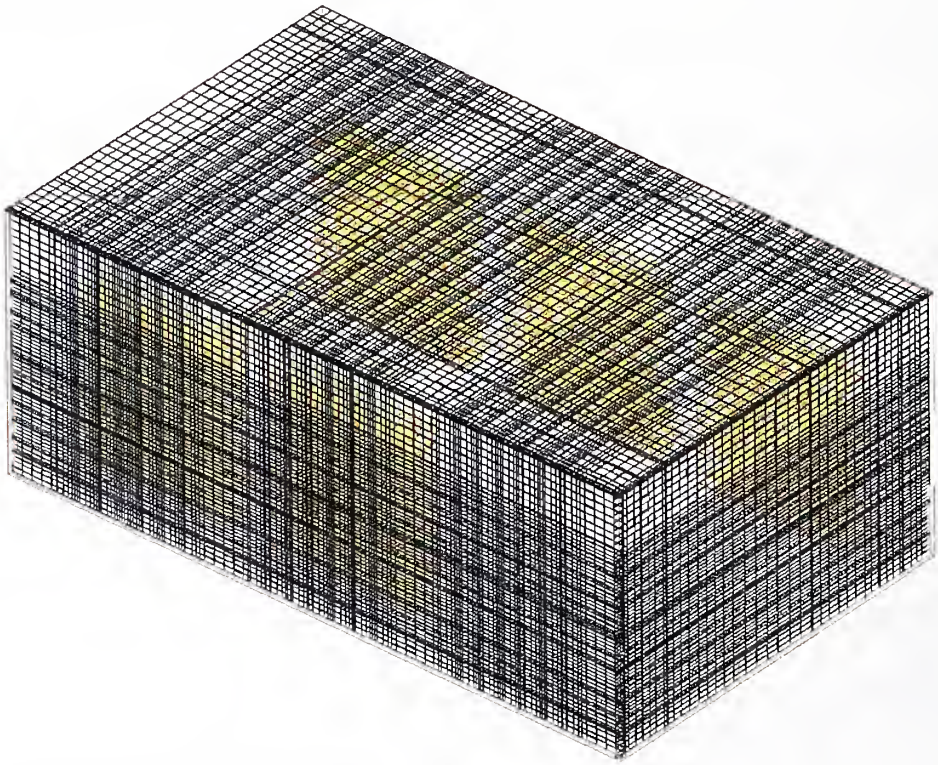

Figure 5.02 *Control Volume Cells*

Note that the solution for each variable will depend on the solution for each and every variable in the *neighboring cells and vice versa.* The laws of physics based upon the *conservation of mass, conservation of momentum, and conservation of energy* must be preserved at all times. In this approach, turbulence is modeled using the established and robust two parameter method known as the k-epsilon model where k represents the kinetic energy and epsilon represents the rate of dissipation.

The mathematical solution is highly iterative, with each iteration resulting in a set of errors. At the end of each iteration the errors for each variable are summed, normalized with an acceptable error, and plotted against iteration number (figure 5.03). A solution is reached when the sums of the errors for each, and all the variables, reaches a pre-determined and acceptable level.

Each cell within the solution domain has eight equations associated with it: pressure, three velocities, temperature, two turbulence quantities, and concentration. An animal room model in this research typically has 100,000 to 600,000 cells, resulting in 4.8 to 6.4 million equations that have to be solved iteratively until the convergence criteria are satisfied. This extremely computer-intensive operation requires the use of powerful state-of-the-art workstations.

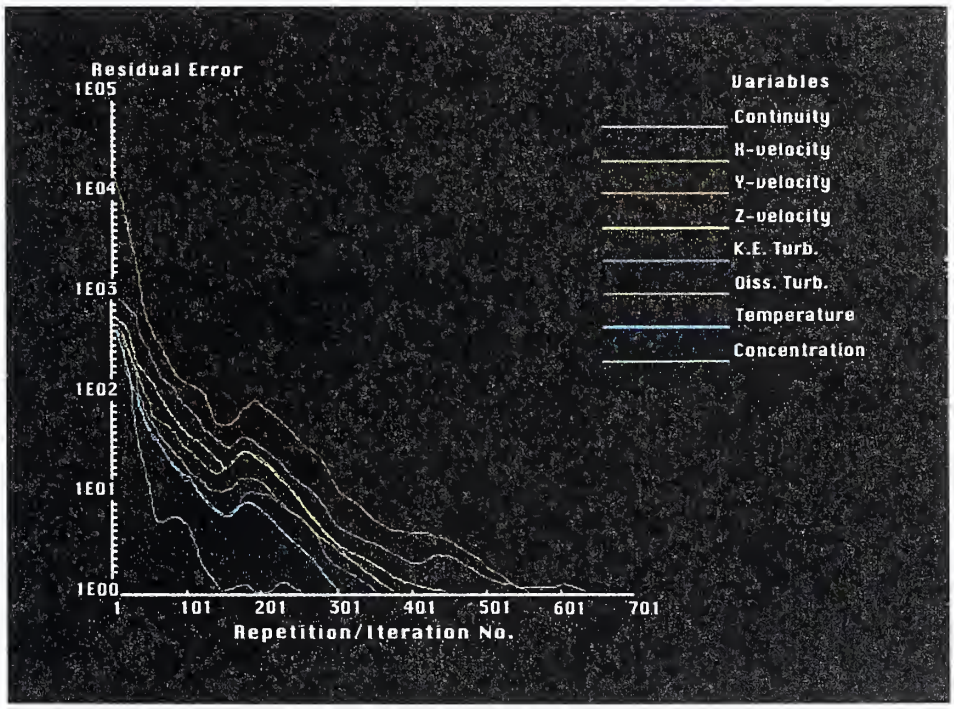

Figure 5.03 *Iterative Convergence History of a Simulation*

5.2 Description of Mathematical Model

5.2.1 Governing Equations

The generic form of the governing equations, shown by equation 5.1, can be expanded to form the three fundamental conservation laws that comprise the Navier-Stokes equations. These are

the conservation of mass:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho U_i}{\partial x_i} = 0 \tag{5.2}$$

the conservation of momentum:

$$\frac{\partial \rho U_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho U_i U_j\right) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial U_i}{\partial x_j}\right) + g_i\left(\rho - \rho_0\right) \tag{5.3}$$

and the conservation of thermal energy:

$$\frac{\partial \rho H}{\partial t} + \frac{\partial}{\partial x_i}\left(\rho U_i H\right) = \frac{\partial}{\partial x_i}\left(\lambda \frac{\partial T}{\partial x_i}\right) + \frac{\partial P}{\partial t} \tag{5.4}$$

These equations describe the behavior of fluids under both laminar and turbulent flow conditions. When calculating the flow in the built environment, one of the most important physical effects is that of turbulence.

5.2.2 Turbulence Modeling

For this project, an established and reliable approach to turbulence modeling is required to achieve the large number of calculations necessary for analysis of the many configurations. This section provides some background on the different approaches to modeling turbulence.

To model a turbulent flow, the temporal terms of equations 5.2, 5.3, and 5.4 would have to have a time step (dt) small enough to capture all turbulent fluctuations on even the smallest time scales. The same applies to all physical dimensions of the control volume cells (dx_i) terms. They would have to be as small as that known as the Kolmogarov scale, which decreases nonlinearly with an increase in Reynolds number.

To overcome these limitations, variables are split into a mean and fluctuating component, i.e.:

$$U = \overline{U} + u'$$
$$H = \overline{H} + h' \tag{5.5}$$

These are then substituted back into the instantaneous momentum equation, producing the following:

$$\frac{\partial}{\partial x_j}\left(\rho \overline{U}_i \overline{U}_j\right) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial \overline{U}_i}{\partial x_j} - \rho \overline{u_i' u_j'}\right) + g_i\left(\rho - \rho_0\right) \tag{5.6}$$

This is known as the time averaged momentum equation. A similar equation exists for the enthalpy equation:

$$\frac{\partial}{\partial x_i}\left(\rho \overline{U}_i \overline{H}\right) = \frac{\partial}{\partial x_i}\left(\lambda \frac{\partial \overline{T}}{\partial x_i} - \rho \overline{u_i' h'}\right) \tag{5.7}$$

The extra terms produced by this substitution are:

- Reynolds stress = $\rho \overline{u_i' u_j'}$
- Reynolds flux = $\rho \overline{u_i' h'}$

A turbulent flow is characterized by the dominance of diffusion due to the Reynolds stresses and the fluxes over the diffusion due to laminar viscosity or laminar diffusivity of the fluid. The spread of contaminants in the animal room, in particular the determination of CO_2 and NH_3 levels in both the cages and within the room itself, is controlled strongly by the diffusion of the contaminant into the surrounding air volume. The role of turbulence modeling, to calculate the Reynolds stresses and fluxes, is therefore of vital importance in the accurate prediction of concentration spread in the cages and room.

The introduction of the Reynolds stresses and fluxes after decomposition of the turbulent fluctuating variables means that the equation set is now not closed. Some form of closure is required to model these fluxes and stresses. There have been a wide range of methods used to do this, varying from the most simple zero-equation models to the much more complex Reynolds stress transport equations. Figure 5.04 shows how these turbulence models relate to each other.

At the center of the zero-, one-, and two-equation models lies the analogy that where a laminar stress exists, so can an equivalent turbulent stress (i.e., Reynolds stress). A laminar shear stress is defined as:

$$\tau = \mu \frac{\partial U_i}{\partial x_j} \tag{5.8}$$

So, if a fluid can have a laminar viscosity, μ, then a turbulent flow should have a turbulent or eddy viscosity, μ_T. By using the eddy viscosity hypothesis that Boussinesq proposed, we can relate the Reynolds stress to the mean strain by:

$$-\rho\overline{u_i'u_j'} = \mu_T\left(\frac{\partial \overline{U}_i}{\partial x_j} + \frac{\partial \overline{U}_j}{\partial x_i}\right) - \tfrac{2}{3}\rho k \partial_{ij} \tag{5.9}$$

A zero-equation turbulence model simply sets a constant value of the eddy viscosity, or deduces it as an algebraic function of flow parameters. A one-equation model uses a differential equation to predict one part of the eddy viscosity while a two-equation model uses two differential equations.

The main limitation imposed at this stage by equation 5.9 is that the eddy viscosity is the same in all directions at any point. Where this may be true of laminar viscosity, which is a property of the fluid, it may not be true of turbulent viscosity, which is effectively a property of the flow. Therefore, this eddy viscosity can have differing values in relation to differing Reynolds stresses. This occurs when the turbulence is said to be anisotropic. Conditions that may cause anisotropy, and thus could invalidate the isotropic assumption of equation 5.9, include extreme streamline curvature, swirl, adverse pressure gradients, and buoyancy.

The two-equation approach including the standard k-ε model and the RNG k-ε model variant is presented first. Reynolds stress modeling is then discussed and, finally, the modeling of the Reynolds fluxes is briefly outlined.

$$\frac{\partial}{\partial x_j}\left(\rho \overline{U}_i \overline{U}_j\right) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial \overline{U}_i}{\partial x_j} - \rho \overline{u_i' u_j'}\right) + g_i(\rho - \rho_0)$$

EDDY VISCOSITY ASSUMPTION

$$-\rho \overline{u_i' u_j'} = \mu_T \left(\frac{\partial \overline{U}_i}{\partial x_j} + \frac{\partial \overline{U}_j}{\partial x_i}\right) - \tfrac{2}{3}\rho k \partial_{ij}$$

from dimensional analysis it is shown that:
$\mu_T = \rho \times$ const. $\times$ velocity scale $\times$ length scale

REYNOLDS STRESS MODELS

the Reynolds stresses are each derived from their own transport equations

ZERO EQUATION

$\mu_T =$ constant *or* an algebraic function of a flow parameter such as Reynolds number

ONE EQUATION MODELS

$$\mu_T = \rho C_\mu \sqrt{k} l$$

the velocity scale, k, is derived from its own transport equation and the length scale, l, is assumed constant

TWO EQUATION MODELS

both the velocity scale, k, as well as a length scale, ε, are derived from their own transport equations

Figure 5.04 *Tree of Turbulence Modeling*

5.2.2.1 k-ε turbulence model

This turbulence model calculates two variables; the kinetic energy of turbulence (k) and the dissipation rate of k (denoted ε).

The eddy viscosity is defined from dimensional analysis as:

$$\mu_T = C_\mu \rho \frac{k^2}{\varepsilon} \tag{5.10}$$

The transport equations for k and ε are:

$$\frac{\partial \rho \overline{U_i} k}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\left(\mu + \frac{\mu_T}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right) + P + G - \rho\varepsilon \tag{5.11}$$

$$\frac{\partial \rho \overline{U_i} \varepsilon}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\left(\mu + \frac{\mu_T}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right) + C_1 \frac{\varepsilon}{k}\left(P + C_3 G\right) - C_2 \rho \frac{\varepsilon^2}{k} \tag{5.12}$$

where P is the shear production, defined as:

$$P = \mu_{eff} \frac{\partial \overline{U_i}}{\partial x_j}\left(\frac{\partial \overline{U_i}}{\partial x_j} + \frac{\partial \overline{U_j}}{\partial x_i}\right) \tag{5.13}$$

G is the production of turbulence kinetic energy due to buoyancy, and is given by:

$$G = \frac{\mu_{eff}}{\sigma_T} \beta g_i \frac{\partial T}{\partial x_i} \tag{5.14}$$

C_μ	0.09
C_1	1.44
C_2	1.92
C_3	1.0
σ_k	1.0
σ_ε	1.217

This model has been tried and tested for a whole range of engineering applications. It is simple, but more importantly, it is *stable*. Only two extra differential equations are introduced. The convergence process is less prone to divergence than other, higher order turbulence models. This approach has been adopted for the present research.

5.2.2.2 *Re-normalized group theory (RNG) kε turbulence model*

Essentially, this model has much the same form as the standard model. It is part empirical and part analytical. The only changes are a modified term relating to the production of energy dissipation in the ε equation and a different set of model constants. This RNG model is typical of those offered by some commercial, general purpose CFD codes. The new equations for k and ε become:

$$\frac{\partial \rho \overline{U_i} k}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\left(\mu + \frac{\mu_T}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right) + \mathrm{P} + \mathrm{G} - \rho\varepsilon \tag{5.15}$$

$$\frac{\partial \rho \overline{U_i} \varepsilon}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\left(\mu + \frac{\mu_T}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right) + \left(C_1 - C_{1\mathrm{RNG}}\right)\frac{\varepsilon}{k}\left(\mathrm{P} + C_3\mathrm{G}\right) - C_2\rho\frac{\varepsilon^2}{k} \tag{5.16}$$

The new function C_{1RNG} is given by the equations:

$$C_{1\mathrm{RNG}} = \frac{\eta\left(1 - \eta/\eta_0\right)}{\left(1 + \beta\eta^3\right)} \tag{5.17}$$

and:

$$\eta = \frac{\mathrm{k}}{\varepsilon}\sqrt{\frac{\mathrm{P}}{\mu}} \tag{5.18}$$

In this case η_0 and β are additional model constants. The latter should not be confused with the coefficient of thermal expansion. The main modification is to the ε equation, where the rate of strain of the flow has been incorporated into the model constants. Under conditions of extreme strain, the eddy viscosity is reduced. It is this feature of the RNG model that is said to accommodate *strong* anisotropy in regions of large shear, i.e., the treatment of massive separation and anisotropic large-scale eddies. Most validation of this model has been only under extremely high strain conditions, such as internal flow in a 180° bend and flow within a contracting-expanding duct. Accurate prediction of separation regions seems to be the grail of the

validation work. A more realistic range of *softer* type flows (i.e., less extreme strain) has not been studied with the RNG model. The infancy of this approach prevents it from being incorporated at this stage. When the model becomes as tried and trusted as the present standard k-ε model, it will be given greater attention.

5.2.2.3 Reynolds stress models (second order closure models)

Instead of employing the eddy viscosity assumption, which assumes an equal eddy viscosity in all three spatial directions, a Reynolds stress model has an equation for each of the six Reynolds stresses themselves. This allows the modeling of the transport of each of these individual stresses. This is the most complex of all models and suffers accordingly. Instead of two extra equations we now have an extra seven. An equation for ε is still required because it pops up in the stress transport equations. Convergence stability now becomes a serious problem. Even if convergence is achieved, it normally takes considerably longer than with a two-equation model. Prescription of boundary conditions is also tricky. Instead of setting just k and ε, we now have to set values at supply boundaries of all stresses, not the easiest of parameters to obtain from experimental measurement. The question has to be asked as to whether the added theoretical capabilities of an RSM are worth the increased solution time and decrease in stability.

5.2.2.4 Modeling of Reynolds fluxes:

The velocity-enthalpy correlations known as the Reynolds fluxes use much the same methodology as the Reynolds stresses. An eddy diffusivity is therefore defined as:

$$-\rho\overline{u_i'h'} = \Gamma_T\left(\frac{\partial \overline{T}}{\partial x_i}\right) \tag{5.19}$$

where this eddy diffusivity is related to the eddy viscosity by:

$$\Gamma_T = \frac{\mu_T}{\sigma_T} \tag{5.20}$$

where σ_T is the turbulent Prandtl number having a fixed value of 0.9. The next step up, as with a second order closure model, is to calculate each of the three fluxes from their own transport equations.

5.2.3. *Near Wall Treatment*

Fluid velocity at a wall surface is zero, which is known as the no-slip condition. The type of flow between the wall and the bulk flow is known as a shear layer, in this case, a wall boundary layer. The boundary layer is a very complex region of high velocity gradient and diffusion dominated development. To model it precisely would necessitate an extremely fine grid. An empirical relationship is therefore used to describe the shape of the boundary layer so that only one grid cell near the wall is required. This empirical relationship describes the shape of the boundary layer in nondimensional terms. Two nondimensional terms are formulated. These are the friction velocity:

$$u_\tau = \left(\frac{\tau_w}{\rho}\right)^{1/2} \tag{5.21}$$

and a nondimensionalized distance from the wall (which can be viewed as a local Reynolds number):

$$y^+ = \frac{u_\tau y \rho}{\mu} \tag{5.22}$$

These formulae are based upon the established 'universal' relationships:

$$\text{For } y^+ > 11.5 \text{ (turbulent): } \frac{u}{u_\tau} = \frac{1}{0.435}\ln\left(9y^+\right) \tag{5.23}$$

$$\text{For } y^+ < 11.5 \text{ (laminar): } \frac{u}{u_\tau} = y^+ \tag{5.24}$$

All that is required to deduce the wall shear stress from the near wall velocity is therefore the distance from the near wall cell center to the wall itself.

5.2.4 *Treatment of Contaminant*

A contaminant that is both advected and diffused by the fluid in which it is suspended can be modeled via the introduction of an additional transport equation. This concentration variable, C, has the units of kg of species/kg of fluid, and obeys the time averaged equation of the conservation of concentration flux such that:

$$\frac{\partial}{\partial x_i}\left(\rho \overline{U}_i \overline{C}\right) = \frac{\partial}{\partial x_i}\left(D\frac{\partial \overline{C}}{\partial x_i} - \rho \overline{u_i' c'}\right) \tag{5.25}$$

The velocity/concentration correlation, like the equivalent velocity/enthalpy correlation of equation 5.17, also follows a gradient hypothesis. In this case turbulent concentration diffusivity is calculated by:

$$D_T = \frac{\mu_T}{Sc_T} \tag{5.26}$$

Both the laminar and turbulent Schmidt numbers have a value of 1.0.

In this project, levels of the two considered animal emission gases, namely CO2 and NH3, were determined by the analysis of the distribution of such a concentration throughout the cages and room volume.

In the cases where the whole animal room was considered, the levels of CO2 and NH3 generated by the animals were small enough such that the concentration could be represented as a passive concentration. In particular, the density change produced by the presence of the gases could be considered insignificantly small. However, in the cage wind tunnel simulations, the level of CO2 injected into the cages was such that the gas affected the density of the gas/air mixture. The density of the gas/air mixture in these cases was calculated as follows:

The density formula is based on the Ideal Gas Law:

$$Density = \frac{effective_molecular_weight \times (T + \text{datum_pressure})}{R \times (T + \text{datum_temperature})} \tag{5.27}$$

where R (universal gas constant) = 8314.4
datum_pressure = 1.0133E5 Pa
datum_temperature = 273.13 K

When the molecular weight of the concentration is different to that of the air, the effective molecular weight is calculated as:

$$\frac{1}{effective_molecular_weight} = \frac{f}{\text{concentration_molecular_weight}} + \frac{1-f}{\text{concentration_molecular_weight}} \tag{5.28}$$

where f is the concentration value

This reduces to the normal Ideal Gas Law when the molecular weight of the concentration is the same as that of the air.

The harmonic average comes about by considering the volume that 1Kg of the mixture occupies namely:

$$\frac{1}{effective_density} = \frac{f}{\text{concentration_density}} + \frac{1-f}{\text{air_density}} \tag{5.29}$$

5.2.5 *Integration of the Governing Equations*

The governing PDE's have to be integrated, or discretized, over the solution grid so that the finite values of the flow variables may be predicted at each cell. The discretization process converts the governing PDE's into algebraic equations. The following figure shows the cell notation that is to be used:

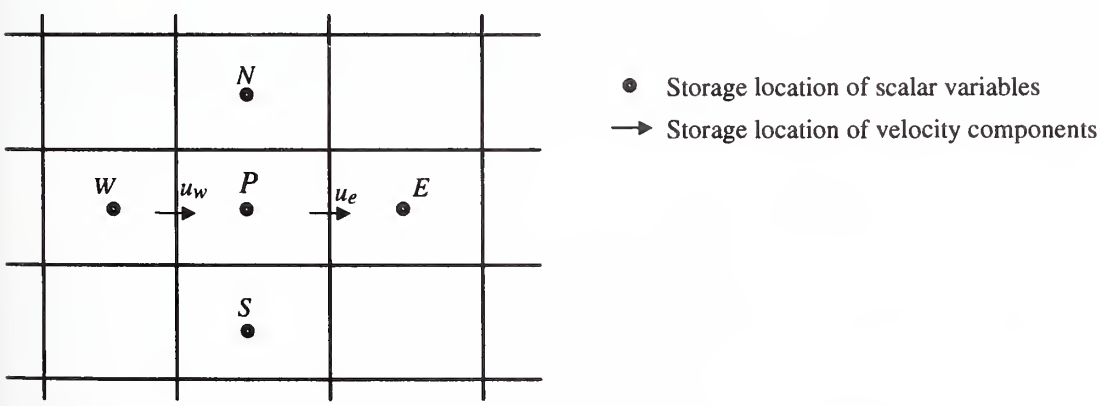

Figure 5.05 *Cell notation*

In this figure we see that all scalar variables are stored at the center of each cell, or rather the scalar variable has the same value throughout that entire cell. The vector variables are stored on

the center of each face of the cell so that fluxes flowing through the cell can be calculated directly.

Once the solution domain has been gridded, each governing equation must be integrated over each cell. Only when the laws of conservation, as well as the turbulent transport equations, are satisfied at each cell (within a tolerable degree) is the solution complete.

For simplicity of coding, all the governing equations are organized into a similar form. This generic form can be written as:

$$\frac{\partial \rho \overline{U_i} \phi}{\partial x_i} - \frac{\partial}{\partial x_i}\left(\Gamma \frac{\partial \phi}{\partial x_j}\right) = S \tag{5.30}$$

The first term represents the convection of any variable, ϕ, by the mean fluid velocity, $\overline{U_i}$; the second term represents diffusion where Γ is the diffusion coefficient; and the third term is a source or sink term where ϕ is either created or destroyed. When integrating over a control volume we obtain:

$$\int \rho \phi \overline{U_i}.\mathbf{n}dA - \int \Gamma \frac{\partial \phi}{\partial x_j}.\mathbf{n}dA = \int S dV \tag{5.31}$$

The calculation of these integrals is the center of the discretization process. Figure 5.05 shows a single orthogonal cell and some of its neighbors. With a nonstaggered grid, all variables are stored at the center of the cell at point P. Neighboring points include points E, W, WW, and so on. In the schemes that follow, a lower case subscript (n, e, s, w) refers to values at the appropriate face whereas an upper case subscript (N, E, S, W) refers to values at the appropriate cell centers.

5.2.5.1 Treatment of the diffusion terms

The diffusion term is the simplest to integrate. By looking at the diffusive flux at the west face of the cell we can write:

$$\int \Gamma \frac{\partial \phi}{\partial x_j}.\mathbf{n}dA = \frac{\Gamma A_w}{h_w}(\phi_P - \phi_W) \tag{5.32}$$

Where h_w is the distance between cell centers. The above equation can be rewritten as:

$$\frac{\Gamma A_w}{h_w}(\phi_P - \phi_W) = D_W(\phi_P - \phi_W) \tag{5.33}$$

Such that D_W is the west-face diffusion coefficient. There is a diffusion coefficient for each face of the cell.

5.2.5.2 *Treatment of the convective terms*

The integration of the convective (sometimes referred to as advective) term is achieved by employing the upwind differencing scheme. Here, the value of the flow variable at a cell interface is equal to the flow variable on the *upwind* side of the face. Consider convection through the west face of the cell (where the fluid enters from the west neighboring cell):

$$\int \rho\phi\overline{U_i}.\mathbf{n}dA = \rho\overline{U_w}A_w\phi_W \equiv F_W\phi_W \tag{5.34}$$

Such that F_W is the west face convection coefficient. Again, there are convection coefficients for each face of the cell.

By combining the effects of both convection and diffusion the finite volume equation is formulated:

$$a_P\phi_P = \sum_{nn} a_{nn}\phi_{nn} + S \tag{5.35}$$

The coefficients (a_P etc.) that express the contribution of convection and diffusion across the cell boundaries are called matrix coefficients. Each matrix coefficient is simply the sum of both diffusion and convection coefficients. The value of the convection coefficient is determined by the direction from which fluid enters the cell.

5.2.6 *Solution of the Finite Volume Equations*

Having covered the derivation of all linearized equations from the governing partial differential equations, the process by which they are solved will now be explained. An iterative process is used, starting from an initial estimate of the values of all variables at each cell through to the converged solution where the final values obey their respective conservation equations to within an acceptable degree of accuracy.

The solution process consists of two loops. An initial guess, or initial condition, is taken for the values of all variables at each cell. The two loops are then iterated in a nested manner. The inner

loop solves the linearized equations for each variable in turn at each cell, assuming all other fields are fixed. The outer loop involves updating all variable fields with the values calculated in the inner loop. As this process progresses, the flow field approaches its final or converged state. The iterative process stops when the errors in all governing equations reach acceptably small values.

5.2.6.1 The inner iteration

The inner iteration consists of taking each variable in turn, while assuming all the others to be fixed, passing the relevant equations for each cell to a Gauss Siedel equation solver. All updated variable values are not passed on to the other linearized equations until completion of the inner loop, and it is within the outer loop that this takes place.

At some point the iterative process must be terminated so that the inner iteration can proceed onto the next variable. Criterion must be met before the inner iterations for a given variable stops. Either the total number of inner iterations is reached or the reduction in the residual error (the amount by which the current governing conservation equation is not satisfied) for the given variable reaches a tenth of the level when the inner iteration began.

5.2.6.2 The outer iteration

Once the inner loop has been completed, i.e., each variable taken in turn and iteratively solved until the stopping criterion has been met, the outer iteration is performed. The main aim of the outer loop is to update all variables in all equations by the values calculated in the inner loop. It is within this outer loop that the velocity–pressure–coupling algorithm, SIMPLE, is implemented. This predicts the correct value for cell pressure based on the current cell momentum (Patankar, 1980).

The outer loop is stopped when the problem is said to have converged. This occurs when the residual errors for all equations are acceptably small (i.e., 0.5 percent of the inlet flux for each variable).

5.3 Nomenclature

ϕ' Fluctuating component of variable ϕ
$\bar{\phi}$ Mean component of variable ϕ
∂_{ij} Kronecker delta (1 if $i = j$ else = 0)
β Coefficient of thermal expansion
ρ Density
ε Rate of dissipation of turbulence energy
τ Shear stress
λ Thermal diffusivity
μ Viscosity
σ_T Turbulent Prandtl number
μ_{eff} Effective viscosity ($\mu + \mu_T$)
Γ_T Eddy diffusivity
μ_T Eddy viscosity
$C_{1\text{-}3,\mu}$ σ_k σ_ε Turbulence model constant(s)
g Acceleration due to gravity
H Enthalpy
k Turbulence energy
P Pressure
T Temperature
U_i Velocity tensor
x_i Distance tensor

SECTION VI

STATISTICAL ANALYSIS

SECTION VI: TABLE OF CONTENTS

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6. STATISTICAL ANALYSIS

6.1 Introduction to Tests of Significance

The normal distribution of individual scores and the understanding of standard deviation are key elements to understanding significance tests. Therefore, a brief review is in order.

6.1.1 Mean

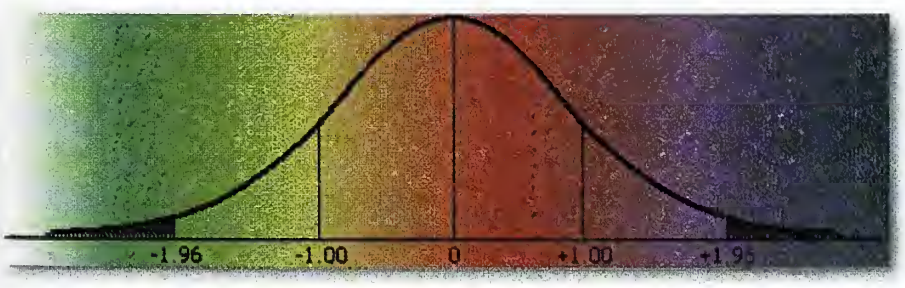
The mean is defined as the sum of scores divided by the number of scores.

6.1.3 Standard Deviation

The standard deviation is the square root of the average squared deviation from the mean. For example, the standard deviation of the Year 2 Internal Medicine scores was 7.1, therefore, we can conclude that 68 percent of the class fell within plus or minus 7.1 points of the mean. Additionally, we can conclude that 95 percent of the class fell within plus or minus 2 x 7.1 points of the mean.

6.1.4 Z- Score

The z-score, (score-mean)/standard deviation, is often used to express a score in relation to the mean score. Graphs of the normal curve usually depict z-scores along the abscissa of the graph and frequency along the ordinate. In the graph below, the shaded area of the normal curve represents five percent of the distribution. That is, 95 percent of the observations fall between z-scores of -1.96 and +1.96 or, put another way, five percent of the observations fall outside this range.

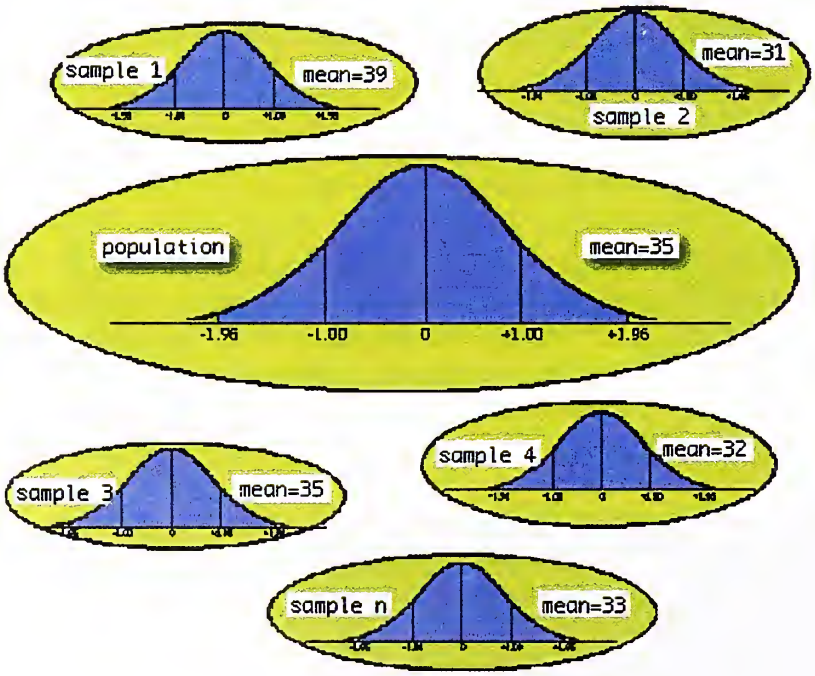


Distribution of Individual Scores

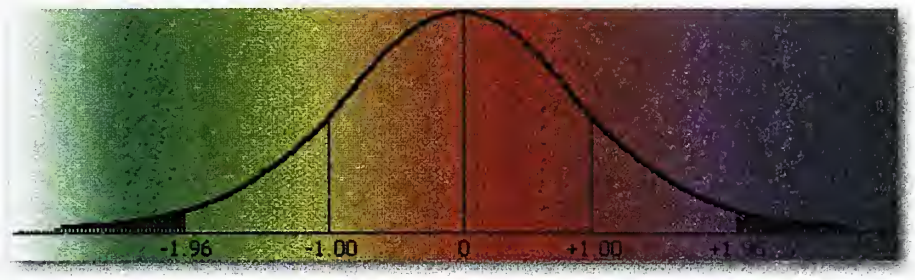
The odds of obtaining a score within -1.96 and +1.96 are 95 out of 100, therefore, the odds of a score being outside that range are five in 100. The latter situation has a probability of less than 0.05, and would use p-value<0.05, to indicate the probability of occurrence. Events which occur only 5 times out of 100 are rare events. These rare events can be considered significant because of their infrequent occurrence.

6.1.5 Standard Error of the Mean

Much of statistics pertains to inferential statistics where we infer population values from sample values. In a typical situation, a sample might be taken and the mean and standard deviation computed. From these data, one will want to infer that the population values are identical or at least similar. In other words, it is hoped that the sample data reflects the population data. Considering a situation in which many samples are taken to determine a mean and standard deviation for each sample, the obtained z-score mean values would be distributed in the same normal distribution as the raw z-scores. Consider the illustration below. Conceptualize a large population where the mean score on a test is 35. Samples drawn from the population would yield different sample means.



The same normal curve graph can be applied to the z-score means that was applied to the individual scores. For example, 95 percent of the z-score means would fall within the range of -1.96 to +1.96.



Distribution of Sample Means

Thus, a standard deviation of sample means describes the variability, or spread, of sample means about the true population mean. In most practical situations, however, only one sample mean is available.

The standard error of the mean is calculated by dividing the standard deviation by the square root of the number of observations.

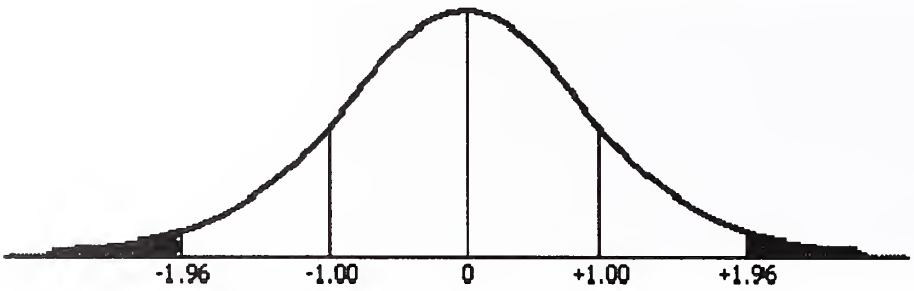
```
standard error of means = standard deviation/square root(n)
```

The resulting estimate of the standard deviation of sample means is called the standard error of means and can be interpreted in a manner similar to the standard deviation of raw scores. For example, the probability of obtaining a sample z-score mean that is outside the -1.96 to +1.96 range is 5 out of 100.

The concept of statistical significance is based on the assumption that events that occur very infrequently by chance are "significant." For example, Tchebysheff's Theorem states that 'given a number k greater than or equal to 1 and a set of n measurements x_1, x_2, x_n, at least $[1-(1/k^2)]$ of the measurements will lie within k standard deviations of their mean'. For example, we expect three out of four values to lie within two standard deviations of the mean and eight out of nine within three standard deviations of the mean.

6.1.6 Standard Error of the Difference

Another situation involves the comparison of two means. Consider a situation where samples are repeatedly drawn from two groups. For example, repeatedly testing male and female groups on a mathematics test, resulting in 100 sample means for male groups and 100 sample means for female groups. Subtracting the male mean from the female mean for 100 pairs of groups will result in 100 differences. A standard deviation of these differences could be computed and interpreted in a manner similar to the standard deviation of scores and to the standard error of the mean.



Distribution of Differences between Two Means

The resulting estimate of the standard deviation of differences between means is called the standard error of the difference and can be interpreted in a manner similar to the standard error of means. For example, the probability of obtaining a difference between means that is outside the -1.96 to +1.96 range is 5 out of 100.

The standard error of the difference is computed by taking the square root of the sum of the standard error of the means (SEM) for group one squared and the standard error of the means for group two squared.

$$\text{standard error of the difference} = \text{square root (group one SEM}^2 + \text{group two SEM}^2)$$

6.1.7 T-Test

The t-test is defined as the difference between the two sample means divided by the standard error of the difference.

$$\text{t-test} = (\text{mean one-mean two})/\text{standard error of the difference}$$

Thus, a t-test result can be interpreted as a z-score. For example, a t-value of 2.4 would be significant, since its probability is less than 5 out of 100. To be precise, the p-values associated with a given t-value depend upon the degrees of freedom that in turn depend upon sample sizes.

The previous formula is for situations in which the samples being compared are independent samples. Other situations arise wherein two measurements are made on the same sample of people. When the two sets of scores are from the same sample, such as in a pre-test/post-test situation, the proper t-test is the t-test for correlated samples (sometimes called the t-test for paired samples or dependent samples).

6.1.8 ANOVA

The standard deviation, t-test, and correlation coefficients involve variance in the concepts and/or calculation methods. Use of the phrase "analysis of variance" (ANOVA) is reserved for a broad range of analytic techniques that address questions of statistical significance through calculation methods that divide overall variance into components. The calculation method uses a technique involving the 'sums of squares.' In one-way ANOVA, the following are calculated: the total sums of squares, sums of squares among groups, and residual sums of squares. Dividing each sums of squares by its associated degrees of freedom results in values called mean squares. Instead of calculating a t-test, ANOVA requires calculation of the F-ratio. Dividing the mean square among groups by the mean square yields the F-ratio. Traditionally, one would consult a table to locate the p-value associated with a specific combination of F, degrees of freedom for groups, and degrees of freedom for the error term. Today's use of computers makes the process of obtaining p-value easy. See T. Lee (1995) for further details.

Table 6.01 shows a sample of a single factor ANOVA test performed on the first three cases (basecase, case 02, and case 03) of this research on the cage occupied zone averaged concentration values. The summary section shows the number of cages in each group, the sum of the concentration values in all cages in a group, the mean average concentration values in all cages in a group, and the variance around the mean. The ANOVA test itself reports an F and an F_{crit} value. If F_{crit} is less than F it can be said that there is a statistical difference between the members of the group. This is true for the sample given below and for all other groups of whole room runs.

Table 6.01 ANOVA Example for Concentration (basecase, case 02, and case 03)

SUMMARY:				
Groups	**Count**	**Sum**	**Average**	**Variance**
Basecase	210	0.5774	0.0027	2.09E-07
Case 02	210	0.4556	0.0022	1.67E-07
Case 03	210	0.4196	0.0020	1.90E-07

ANOVA:						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-Value**	**Fcrit**
Between Groups	6.51E-05	2	3.26E-05	172.3	2.27E-60	3.0101
Within Groups	0.00012	627	1.89E-07			
Total	0.00018	629				

Table 6.02 ANOVA Example for Temperature (basecase, case 02, and case 03)

SUMMARY				
Groups	**Count**	**Sum**	**Average**	**Variance**
Basecase	210	4631.6	22.06	0.1601
Case 02	210	4689.7	22.33	0.0708
Case 03	210	4905.7	23.36	0.2327

ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-Value**	**Fcrit**
Between Groups	198.71	2	99.35	643.0	1.3E-152	3.01
Within Groups	96.89	627	0.155			
Total	295.59	629				

These examples show the F-value is much larger than the F_{crtit} and, therefore, the means are significantly different.

SECTION VII

GLOSSARY OF TERMS

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7. GLOSSARY OF TERMS

7.1 Experimental Terms

Absolute pressure: the sum of the indicated gage pressure plus the atmospheric pressure.

ACH (air changes per hour): the complete replacement of air inside an area; an office or space that has its total air volume replaced in the time period of one hour experiences one air change per hour.

Anemometer: an instrument used to measure air velocities.

Atmospheric pressure: the pressure exerted upon the earth's surface by the air because of the gravitational attraction of the earth, measured with a barometer. Standard atmospheric pressure at sea level is 14.7 pounds per square inch (psi).

Barometer: an instrument for measuring atmospheric pressure.

BTU (British thermal unit): the amount of heat required to raise or lower the temperature of one pound of water 1 °F. 1 BTU = 1,055 Joules.

Calibration: determining or correcting the error of an existing scale.

Calorie: the amount of heat needed to raise the temperature of 1 g of water by 1 °C, from 14.5 to 15.5 °C. A kilocalorie (kilogram-calorie or large calorie) is 1,000 calories.

Calorimeter: the measurement of heat. Heat is one of the most conveniently handled forms of energy. Calorimetry is used to estimate nutritional requirements of humans and farm livestock and to evaluate different foods. It is also a powerful research tool used to study fundamental nutritional and physiological life processes, and to evaluate stresses imposed by abnormal environments. It is used in clinics as a diagnostic tool for the investigation of metabolic disorders.

Capture hood: an instrument that takes the air of a supply, return, or exhaust terminal and guides it over a flow-measuring device. It measures airflow in cubic feet per minute.

Chromatography: a separation method that relies on differences in partitioning behavior between a flowing mobile phase and a stationary phase to separate the components in a mixture.

CFM (cubic feet per minute): a unit of measurement representing the volume or rate of airflow.

Deflecting vane anemometer: a device that gives instantaneous, direct readings in feet per minute, used most often for determining air velocity through supply, return, and exhaust air grilles, registers or diffusers. Attachments are used to measure low velocities in an open space or at the face of a fume hood.

Differential pressure gage: an instrument that reads the difference between two pressures simultaneously, eliminating the need to take two separate pressures and calculate the difference.

Electronic Instruments: most of the mechanical analog instruments now have electronic digital counterparts. All instruments, analog or digital, should be checked against a sheltered set before each balancing project. Pressure measuring instruments should be checked against a standard liquid-filled manometer.

Endotherm: a species that maintains an appreciable difference between body temperature and ambient temperature by virtue of internal (metabolic) production of heat.

FPM (feet per minute): a unit of measurement used for velocity.

Gage: an instrument for measuring pressure.

Gage pressure: the pressure that is indicated on the gage.

Gas chromatography: a chromatographic technique that can be used to separate volatile organic compounds. A gas chromatograph consists of a flowing mobile phase, an injection port, a separation column containing the stationary phase, and a detector. The organic compounds are separated due to differences in their partitioning behavior between the mobile gas phase and the stationary phase in the column.

Homeotherm: species such as mammals and birds that regulate their body temperature physiologically.

Hot wire anemometer: an instrument that measures instantaneous air velocity in feet per minute using an electrically heated wire. As air passes over the wire, the wire's resistance is changed and this change is shown as velocity on the instrument's scale.

Inches of water gage or column: a unit of air pressure using as a reference the pressure exerted by a column of water that is one inch high.

Latent heat: the amount of heat required to convert a quantity of a solid at its melting point into a liquid at the same temperature.

Manometer: an instrument that is the industry standard for reading air pressure. Types of

manometers commonly used to measure air pressure are the inclined manometer, the inclined-vertical manometer, the U-tube manometer, and the micromanometer.

Meniscus: the curved surface of the liquid column in a manometer. In manometers that measure air pressure, the liquid is either water or a light oil. In manometers that measure water pressure, the liquid is mercury.

Metabolic Rate: in comparative physiology, the rate of an animal's energy consumption, that is, the rate at which it converts chemical energy to heat and external work.

Micromanometer: an instrument used to measure very low pressure, accurate down to plus or minus one-thousandth (0.001) inch of water gage.

Operating load point: the actual system operating capacity when an instrument reading is taken.

Parallax: a false reading that occurs when the eye of the reader is not exactly perpendicular to the lines on an instrument scale.

Pitot tube: a sensing device used to measure total pressure in a fluid stream, invented by a French physicist, Henri Pitot, in the 1700's. The standard Pitot tube has a double tube construction with a 90-degree radius bend near the tip and measures both total and static pressures.

Relative humidity: the ratio of the partial pressure of water vapor in moist air to the saturation vapor pressure at the same temperature.

Sensible heat: the amount of heat required to raise the temperature of a solid.

Sensitivity: a measure of the smallest incremental change to which an instrument can respond.

Sheltered set: a set of instruments used only to check the calibration of field instruments.

SCFM (standard cubic feed per minute): the volumetric rate of air flow at standard air conditions.

Thermoneutral zone: a range of environmental temperatures within which the metabolic rate is independent of ambient temperature and is lower in range than any other ambient temperature.

U-tube manometer: a manometer with a U-shaped glass or plastic tube partly filled with oil or tinted water.

7.2 CFD Glossary

Advection: the process by which a quantity of fluid is transferred from one point to another due

to the movement of the fluid.

Boundary condition(s): a term that means either a set of conditions that define a physical problem, or a plane at which a known solution is applied to governing equations.
Boundary layer: a very narrow region next to a solid object in a moving fluid, containing high gradients in velocity.

CFD (computational fluid dynamics): the study of the behavior of fluids using computers to solve the equations that govern fluid flow.

Clustering: increasing the number of grid points in a region to better resolve a geometric or flow feature; increasing the local grid resolution.

Continuum: having properties that vary continuously with position. The air in a room can be thought of as a continuum because any cube of air will behave much like any other cube of air.

Convection: a more generic description of the advection process.

Convergence: a state that is achieved when the imbalances in governing equations fall below an acceptably low level during the solution process.

Diffusion: the process by which a quantity spreads from one point to another due to the existence of a gradient in that variable.

Diffusion, molecular: spreading of a quantity due to molecular interactions within the fluid.

Diffusion, turbulent: spreading of a quantity due to increased mixing rates exhibited by turbulent flows. In the majority of situations, turbulent diffusion far exceeds molecular diffusion.

Divergence: a situation that occurs when the imbalances in governing equations reach unacceptably high levels during the solution process

Eddy viscosity: an additional viscosity that is produced due to the effects of fluid turbulence.

Eddy diffusivity: an additional diffusivity that is produced due to the effects of fluid turbulence.

Far-field distance: the approximate distance from the surface of the body to the farthest point in the Computational Domain. For example, "The wing simulation had a far-field distance of 15 wing chords."

Gauss Siedel equation solve: a method by which linear equations are solved on a cell-by-cell basis.

Gradient: the amount by which a variable changes in space or time.

Grid resolution: the amount of grid points located in a physical area, for example, "The grid uses 20 grid points to resolve the boundary layer."

Near-wall spacing: the distance of the closest point to the surface of a body, an especially important parameter in viscous flow simulations.

Normal stress: the force/unit area that results from one body directly striking another. For instance, slamming your fist down upon a table will cause pain due to normal stress on your hand and the table. Pressure is always a normal stress.

Reynolds number: a nondimensional number that is used to indicate how turbulent the flow of a fluid.

Reynolds stress: the averaged product of two velocity components in turbulence modeling, in which an instantaneous velocity is broken down into mean and fluctuating components.

Reynolds flux: a Reynolds flux, as in a Reynolds stress, is the average product of two fluctuating variable components, one of which is a fluctuating velocity component.

Shear stress: the force/unit area that results from one body sliding relative to another. For example, sliding a book along a table top will cause a shearing stress on both the book and the table top.

Solution domain: the computational volume in which the governing equations, together with the boundary conditions, are solved.

Turbulence: a type of flow that occurs when a fluid is moving quickly and/or within an unconfined space, characterized by a marked increase in mixing where, superimposed on the principle motion, there are countless irregular fluctuations.

Viscosity: a description of thick or heavy flow in the movement of one layer of fluid over another. For example, a viscous fluid like maple syrup will take a long time to pour from a bottle, while beer, which is not as viscous, can be poured quite readily. Viscosity is usually given the Greek symbol "(". Water is approximately 100 times as viscous as air, while most oils are approximately 1,000 times as viscous as water. The effects of viscosity are most easily related to a concept like friction. The viscosity of fluids will cause a resistance to motion, such as a drag that must be overcome by providing more power. If the drag caused by viscosity is small compared to other forces, or if it is important only in a small region like in boundary layer theory, then the effects of viscosity can be ignored. Such a case is called inviscid flow. It is a point of confusion, even for practicing aeronautical engineers, that an inviscid flow is not the flow of a

fluid with zero viscosity, rather an inviscid flow contains negligibly small viscous stresses.

Vorticity: the swirling motion of a fluid. Satellite photographs on the TV news weather forecasts often show large rotating masses of fluid, which are special cases of vortices.

SECTION VIII

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8. REFERENCES

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APPENDIX I

EXPERIMENTAL PROCEDURES AND DATA

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1. INTRODUCTION

This appendix presents various aspects of the experimental stages of this project. The main body of the appendix is split into four sections:

Cage Condition: This section presents calibration procedures, experimental data, and justification of the sizing of the Simulated Mouse Heater (SMO).

CO_2, NH_3, H_20, and Heat Generation Measurements at Low and High Humidities: This section presents an introduction to direct and indirect calorimetry, calibration procedures, measurement procedures, and experimental data, in both tabulated and graphical forms.

Room Conditions: This section presents the justification of air velocity sampling frequency, and justification of steady-state for temperature and air velocity fields.

Photographs from Experimental Test: This section presents a series of photographs from each of the three experimental stages listed above.

2. CAGE CONDITIONS

2.1 Calibration Procedures

2.1.1 Temperature Sensor Calibration for Type T Thermocouples

Fill a temperature regulated water bath approximately 2/3 to 3/4 full of water and heat to first desired temperature.

Place thermocouples about two or three inches below the water surface near to center of the water bath.

Verify water temperature by placing a SAMA thermometer next to the thermocouples.

Monitor water bath temperature with the SAMA thermometer to ensure that it is stable (+/- 1.5 °C) for approximately two minutes before taking each reading.

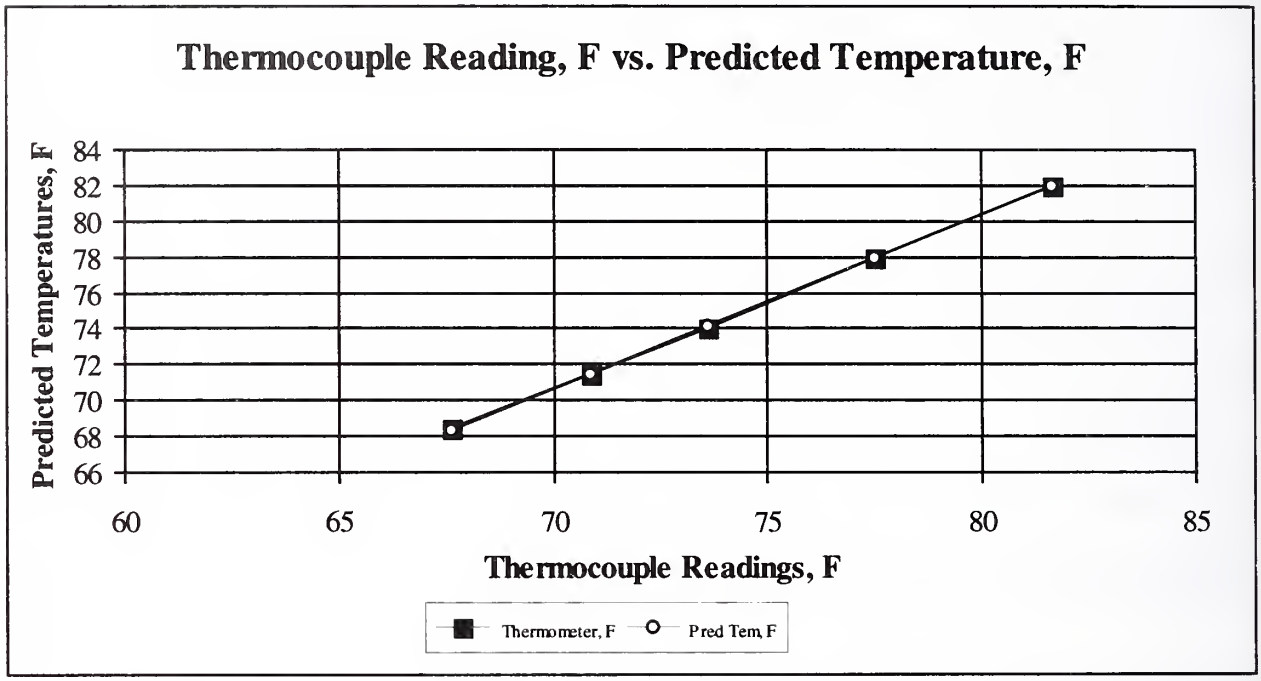
Take the thermocouple reading and record on the attached calibration sheet.

Repeat steps four and five for at least three different temperatures. The mid-calibration temperature should be near the anticipated average experimental temperature. The lowest and highest calibration temperatures should be around 5 °F below and 5 °F above the anticipated temperature range.

2.1.1.1 Typical Calibration Results

Comparison of Thermocouple and Thermometer Results

Thermocouple (°F)	Thermometer (°F)	Pred. Temperature (°F)
67.6	68.5	68.4
70.9	71.5	71.5
73.6	74.0	74.2
77.5	78.0	77.9
81.7	82.0	82.0



2.1.2 Air Velocity Sensor Calibration

Every morning turn on the sink in the back of the fan test chamber. Allow the water to run for at least 10 minutes. This is necessary because the cooling unit will overheat if hot water is introduced into it.

Remove the large duct on top of the blue chamber. Open the damper below it. Replace the duct.

Check the barometric pressure and the zero of the pressure gauge.

Turn on the long gray chamber using the computer
Pick "2" (Controls) [Return]
Pick "1" (Run/Standby) [Return]
Pick "1" (Run) [Return] [Return]

Allow the blue chamber to cool for at least 10 minutes.

Remove the large duct again and open the blue foam damper on it.

Close the damper, which was below it.

Turn on the calibrator fan and adjust it to the desired pressure (listed pressure + zero pressure),

Turn off the environmental test chamber by picking Standby instead of Run. You should hear the compressor turn off if this step is done correctly.

Turn on the Campbell by typing *1A2A*6.

Let the Campbell run for five minutes.

Plug in the heater.

Let the Campbell run until the inside temperature reaches 85 degrees (the first Fahrenheit temperature listed on the Campbell).

Stop the Campbell by pressing *1A0A*7.

Unplug the heater and turn off the calibrator fan.

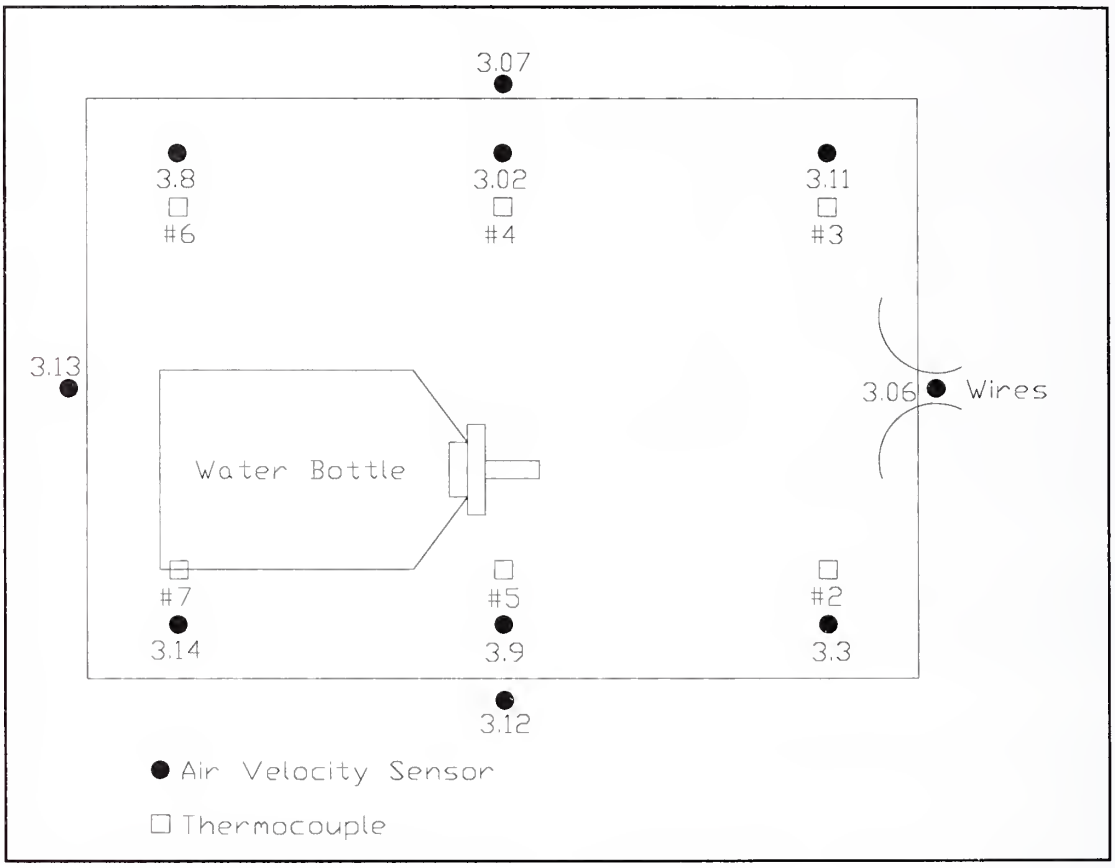
Download the data using the computer. Use the TELCOM program. Name the file in this format: month–day–test#. For example, 3–27–1 would be the first test on March 27.

Clear the Campbell by pressing *AA128A*6.

Repeat steps 2-16 for each velocity.

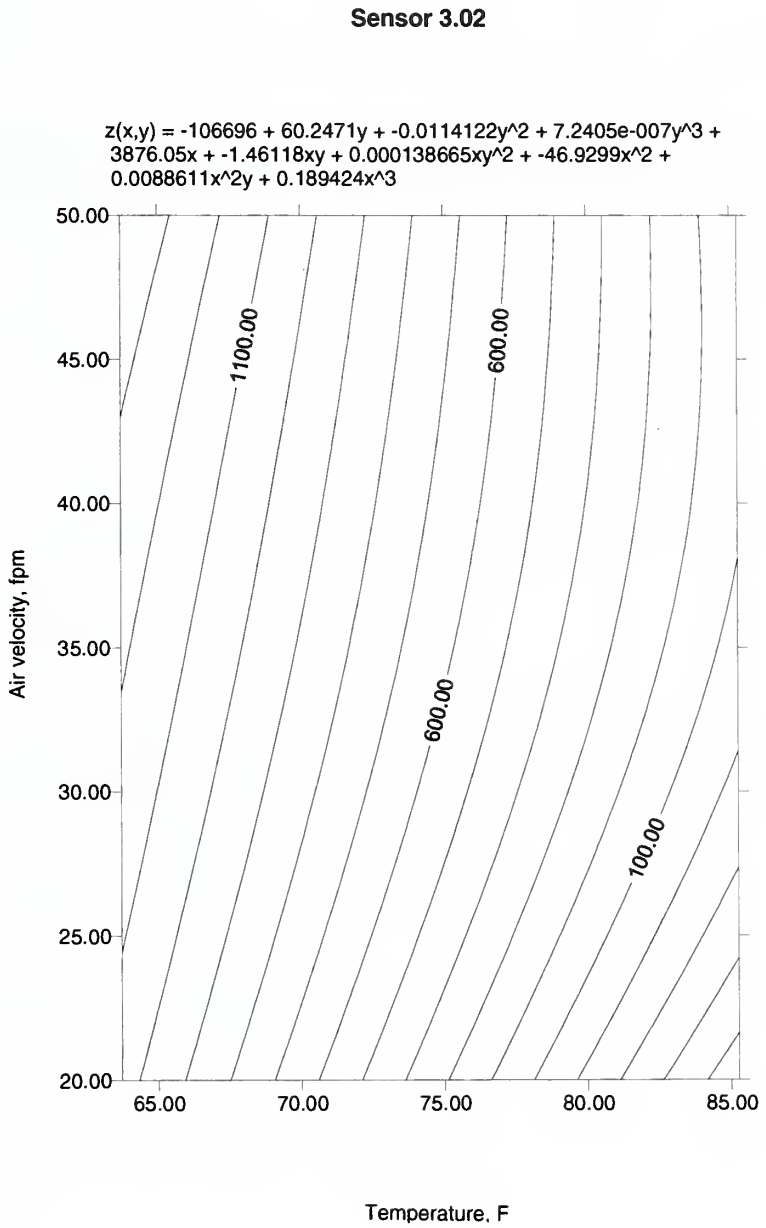
2.1.2.1 Typical Calibration Results

Locations of Velocity Sensors and Thermocouples within the Cage



Temperature and voltage data were analyzed to form trend lines for each velocity. The trend lines were used to generate predicted voltage values. The velocity data, temperature data, and predicted voltage values were then combined and plotted to form a contour map that had axes of velocity, temperature, and contours of voltage. The map was made using a third order polynomial regression. A third order polynomial regression was chosen because it provided an equation that could easily be used to determine velocity values within a spreadsheet and because it displayed contour lines that closely followed those lines displayed by other curve-fit methods. The contour map was made as a visual means of finding if values were not outside the calibration range, i.e. greater than 0.25 m/s (50 fpm) or less than 0.10 m/s (20 fpm).

Typical Contour Map



2.2 Experimental Data

The experimental data sets for the cage condition section of work are summarized below:

Series Set	Tracer Gas	Injection Rate (L/ min)	Sampling Method	Mouse Heater Type	Cage Orientation	Tunnel Air Velocity Range (fpm)
Base	CO_2	1.0	Steady	DMH (On/ Off)	Par, Perp, Vert	15 – 100
One	CO_2	0.1	Steady	DMH (On only)	Par, Perp	15 – 50
Two	SF_6	0.1	Steady	DMH (On only)	Par, Perp	15 – 50
Three	CO_2	0.1	Steady	DMH (On/ Off)	Par, Perp, Vert	20, 40
Four	CO_2	0.1	Steady	SMO (On only)	Par, Perp, Vert	20, 30, 40
Five	CO_2	0.1	Decay	SMO (On only)	Par, Perp, Vert	20, 30, 40
Six	CO_2	0.1	Steady	DMH (On/ Off); SMO (On Only)	Par, Perp	20,40
Seven	CO_2	0.1	Steady	DMH (On/ Off); SMO (On Only)	Par, Perp	20, 40
Eight	CO_2	0.1	Steady	SMO (On Only)	Par, Perp	30

2.2.1 *Series Set Base*

Parallel Cage Orientation

Tabulated Data:

Air Vel.	Bar Pres	Temp	F CO_2	B CO_2	K	CFM (w/o K)	CFM (w/K)	Pred. CFM	Act./Pred
15	29.40	72.0	15.56	0.23	0.98	0.19	0.19	0.17	1.11
20	29.39	71.0	15.19	0.24	0.98	0.20	0.20	0.19	1.05
30	29.39	71.5	14.58	0.54	0.98	0.21	0.21	0.22	0.98
40	29.39	72.0	14.02	0.18	0.98	0.22	0.21	0.24	0.88
50	29.13	70.8	11.19	0.08	0.97	0.28	0.27	0.27	1.00
60	29.14	70.5	10.29	0.08	0.97	0.31	0.30	0.30	1.00
70	29.15	70.5	9.50	0.07	0.97	0.34	0.33	0.33	1.00
80	29.37	71.0	9.13	0.37	0.98	0.37	0.36	0.36	1.00
90	29.37	70.0	8.38	0.16	0.98	0.39	0.39	0.39	0.99
100	29.37	70.0	7.55	0.15	0.98	0.44	0.43	0.42	1.04

Perpendicular Cage Orientation

Tabulated Data:

Air Vel.	Bar Pres	Temp	F CO_2	B CO_2	K	CFM w/o K	CFM w/K	Pred. CFM	Act./Pred
15	29.45	71.0	15.53	0.17	0.98	0.19	0.19	0.19	0.99
20	28.29	71.5	15.55	0.21	0.94	0.19	0.18	0.19	0.94
30	29.45	71.5	13.80	0.11	0.98	0.22	0.22	0.20	1.07
40	28.88	71.5	13.56	0.12	0.96	0.23	0.22	0.22	0.99
50	29.41	73.0	11.79	0.27	0.98	0.27	0.26	0.25	1.07
60	29.89	72.0	11.34	0.11	1.00	0.28	0.28	0.28	0.98
70	29.43	73.0	9.95	0.09	0.98	0.32	0.32	0.32	0.97
80	29.43	73.5	8.59	0.06	0.98	0.38	0.37	0.38	0.98
90	29.44	73.0	7.52	0.08	0.98	0.44	0.43	0.44	0.99
100	28.92	71.2	7.01	0.86	0.96	0.53	0.51	0.50	1.02

Vertical Cage Orientation

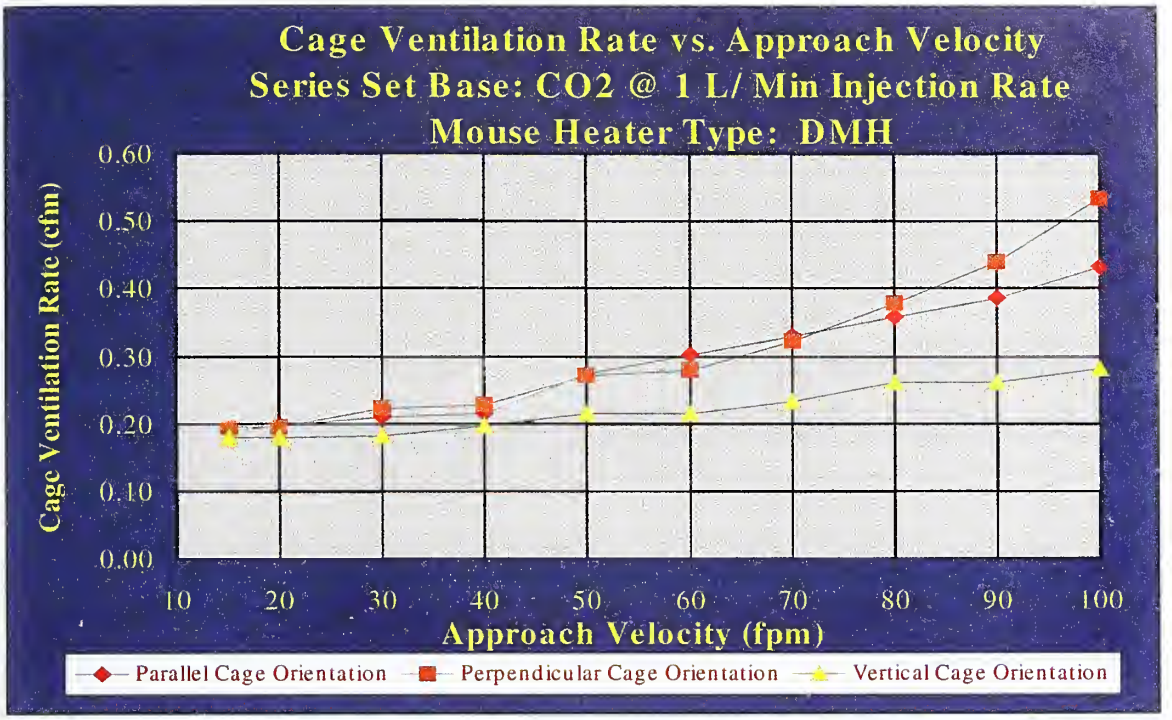
Tabulated Data:

Air Vel.	Bar Pres	Temp	F CO_2	B CO_2	K	CFM w/o K	CFM w/K	Pred. CFM	Act./Pred
15	28.82	71.0	16.00	0.12	0.96	0.19	0.18	0.17	1.06
20	29.21	70.5	16.17	0.07	0.98	0.18	0.18	0.18	1.02
30	28.81	73.0	15.78	0.09	0.96	0.19	0.18	0.19	0.96
40	29.20	74.9	14.87	0.09	0.97	0.20	0.20	0.20	0.98
50	29.25	71.2	13.89	0.07	0.98	0.22	0.21	0.21	1.01
60	28.82	73.5	13.63	0.10	0.96	0.23	0.22	0.23	0.95
70	29.20	71.5	12.85	0.07	0.97	0.24	0.23	0.24	0.98
80	29.20	74.5	11.67	0.08	0.97	0.27	0.26	0.25	1.04
90	28.82	74.9	11.55	0.10	0.95	0.27	0.26	0.26	0.99
100	29.19	71.7	10.88	0.07	0.97	0.29	0.28	0.28	1.02

Where:

Air Vel. - Approach air velocity, fpm
Bar press - Barometric pressure, inches of mercury
Temp - Approach air temperature, F
F CO_2 - Carbon dioxide concentration at sampling tube "F"
B CO_2 - Carbon dioxide concentration at sampling tube "B"
K - K factor for adjusting cage ventilation rate for standard conditions
CFM w/o K - Cage air exchange rate without correction to standard conditions, cfm
CFM w K - Cage air exchange rate with correction to Standard conditions, cfm
Pred. CFM - Predicted cage air exchange based on regression of corrected values, cfm

Graphical Representation:



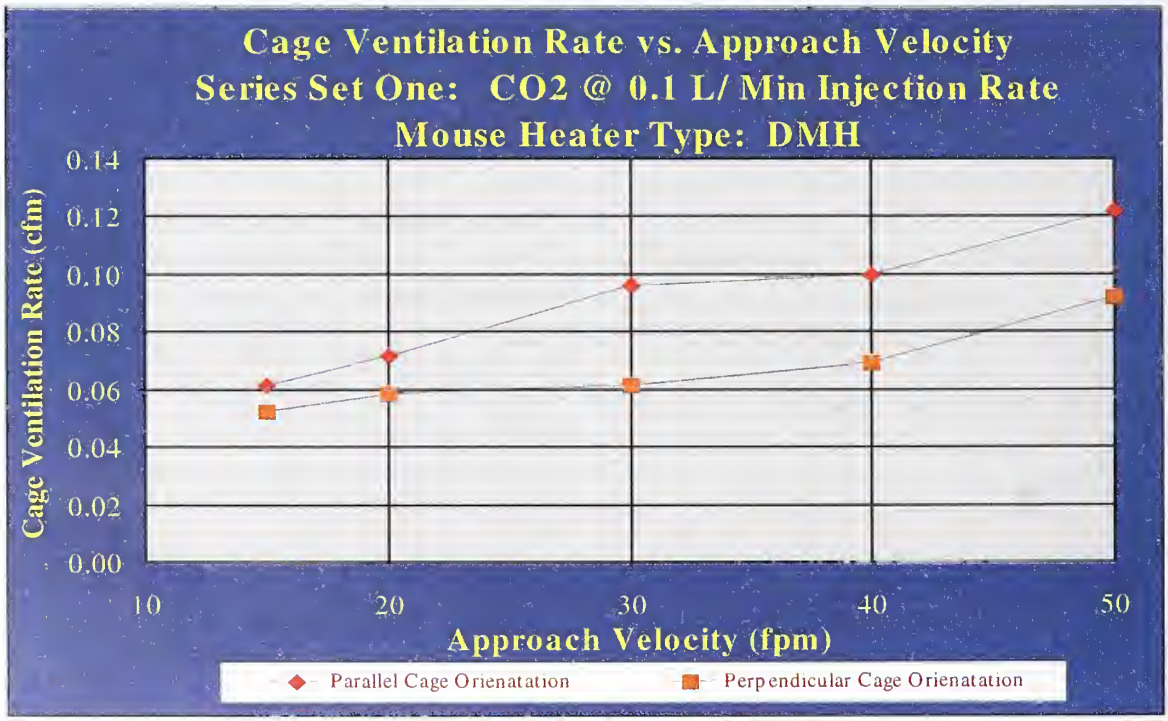
2.2.2 Series Set One - CO_2 used as tracer gas

Parallel Cage Orientation

Desired Air Velocity (fpm)	Temperature Rise in Cage (°F)	Ventilation Rate (cfm)
15	6.02	0.06
20	5.31	0.07
30	5.13	0.10
40	5.19	0.10
50	5.08	0.12

Perpendicular Cage Orientation

Desired Air Velocity (fpm)	Temperature Rise in Cage (°F)	Ventilation Rate (cfm)
15	5.56	0.05
20	5.17	0.06
30	5.96	0.06
40	5.18	0.07
50	4.49	0.09



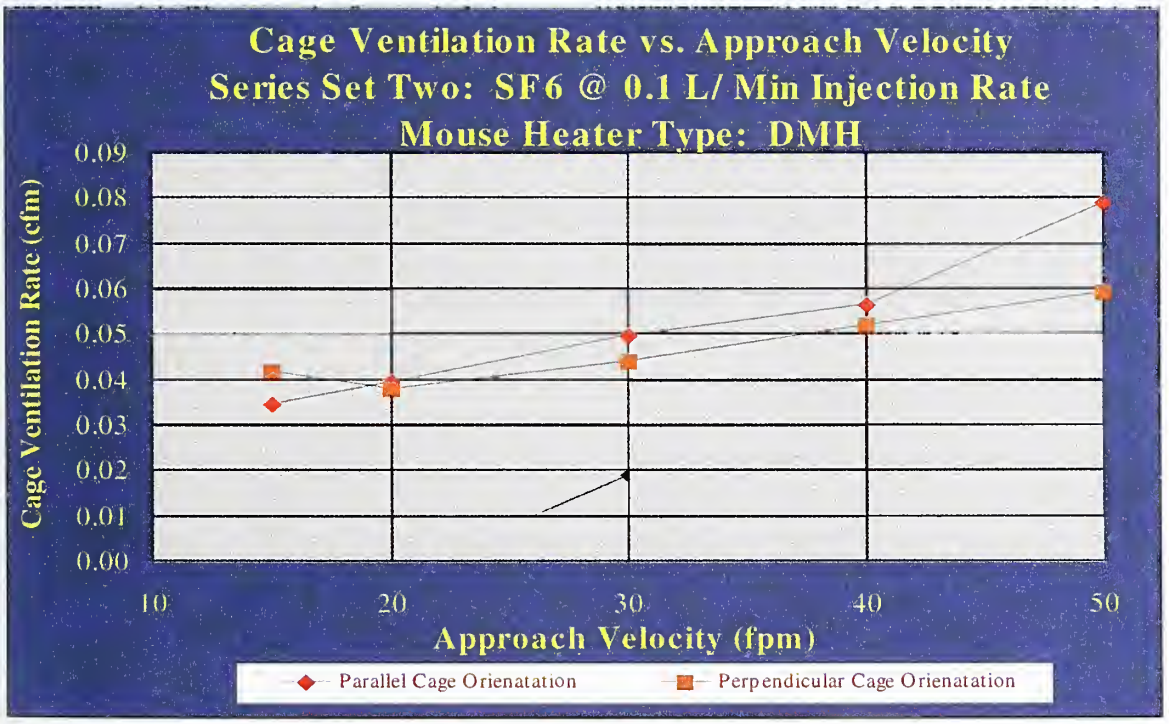
2.2.3 *Series Set Two - SF6 used as tracer gas*

Parallel Cage Orientation

Desired Air Velocity (fpm)	Temperature Rise in Cage (°F)	Ventilation Rate (cfm)
15	2.77	0.04
20	3.97	0.04
30	5.39	0.05
40	5.30	0.06
50	3.72	0.08

Perpendicular Cage Orientation

Desired Air Velocity (fpm)	Temperature Rise in Cage (°F)	Ventilation Rate (cfm)
15	5.42	0.04
20	5.71	0.04
30	4.71	0.04
40	5.05	0.05
50	5.40	0.06



2.2.4 Series Set Three

Parallel Cage Orientation: Heater On

Desired Air Velocity (fpm)	Temperature Rise in Cage (°F)	Ventilation Rate (cfm)
20	3.90	0.08
30	3.00	0.11
40	5.45	0.13

Parallel Cage Orientation: Heater Off

Desired Air Velocity (fpm)	Temperature Rise in Cage (°F)	Ventilation Rate (cfm)
20	2.16	0.09
30	2.63	0.12
40	1.97	0.15

Perpendicular Cage Orientation: Heater On

Desired Air Velocity (fpm)	Temperature Rise in Cage (°F)	Ventilation Rate (cfm)
20	3.78	0.08
30	4.45	0.14
40	3.66	0.24

Perpendicular Cage Orientation: Heater Off

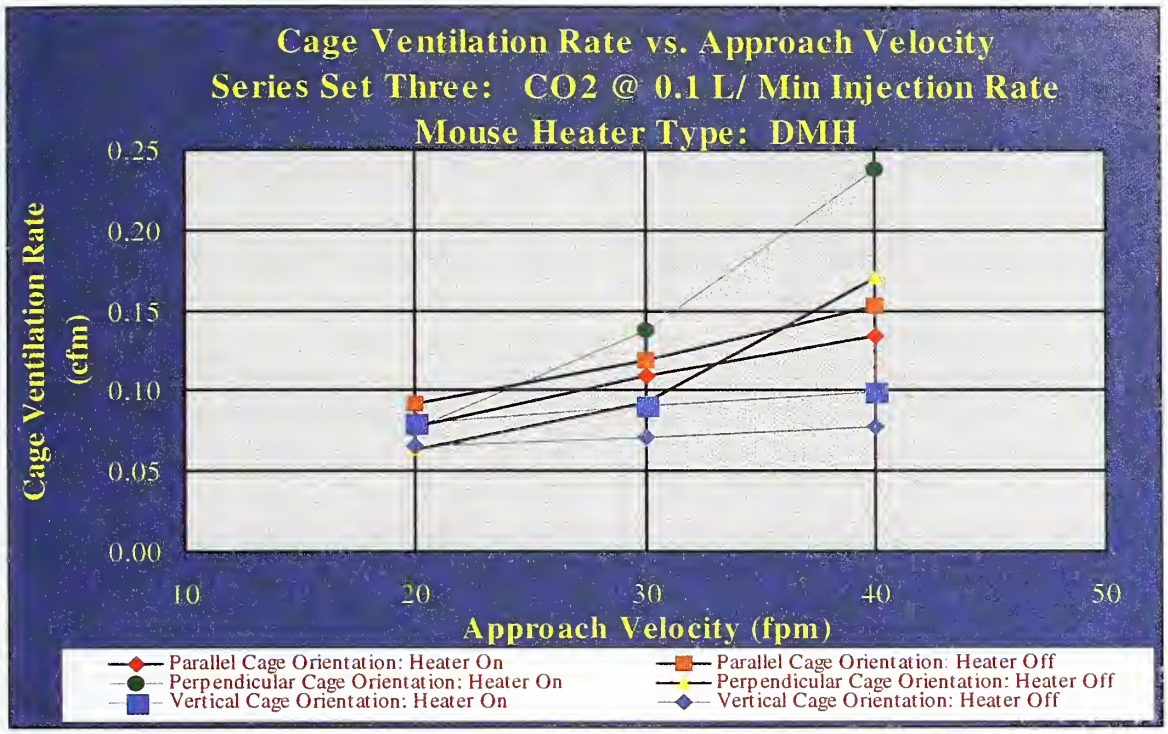
Desired Air Velocity (fpm)	Temperature Rise in Cage (°F)	Ventilation Rate (cfm)
20	3.16	0.06
30	2.37	0.09
40	3.04	0.17

Vertical Cage Orientation: Heater On

Desired Air Velocity (fpm)	Temperature Rise in Cage (°F)	Ventilation Rate (cfm)
20	6.36	0.08
30	4.54	0.09
40	5.66	0.10

Vertical Cage Orientation: Heater Off

Desired Air Velocity (fpm)	Temperature Rise in Cage (°F)	Ventilation Rate (cfm)
20	4.04	0.07
30	4.20	0.07
40	4.95	0.08


Cage Ventilation Rate vs. Approach Velocity
Series Set Three: CO2 @ 0.1 L/ Min Injection Rate
Mouse Heater Type: DMH
Cage Ventilation Rate (cfm)
0.25
0.20
0.15
0.10
0.05
0.00
10
20
30
40
50
Approach Velocity (fpm)
Parallel Cage Orientation: Heater On
Parallel Cage Orientation: Heater Off
Perpendicular Cage Orientation: Heater On
Perpendicular Cage Orientation: Heater Off
Vertical Cage Orientation: Heater On
Vertical Cage Orientation: Heater Off

2.2.5 Series Set Four - Steady State Injection Rate

Parallel Cage Orientation

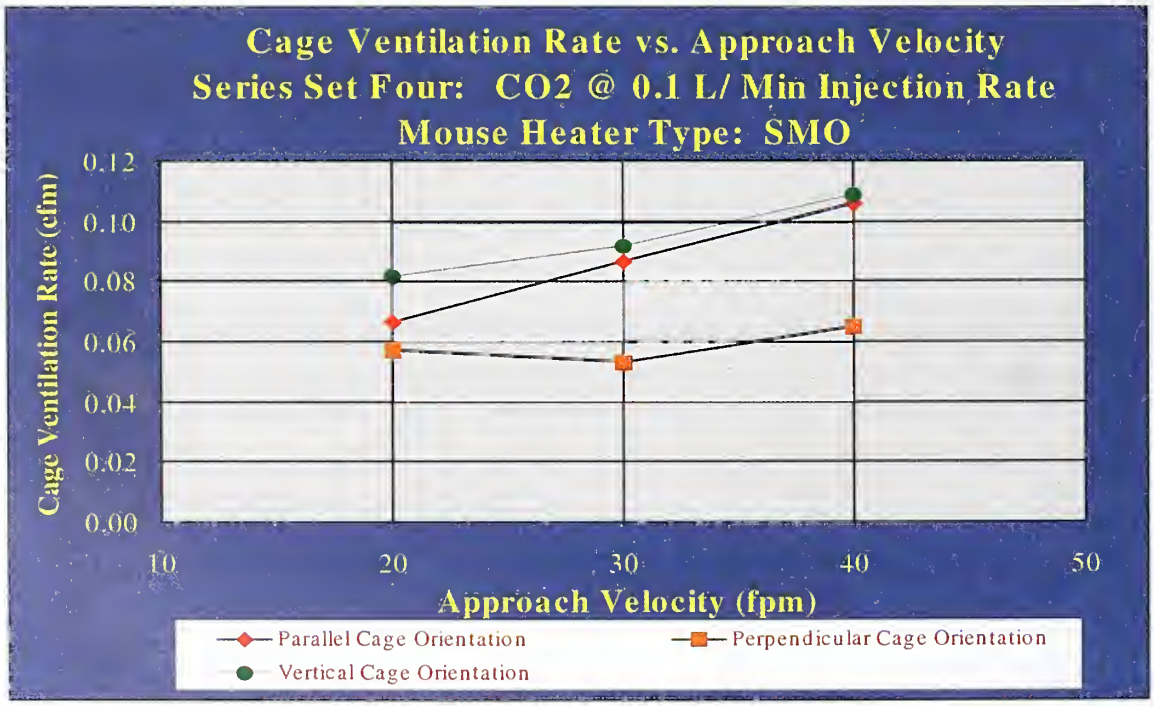
Desired Air Velocity (fpm)	Temperature Rise in Cage (°F)	Ventilation Rate (cfm)
20	7.40	0.07
30	7.36	0.09
40	7.62	0.11

Perpendicular Cage Orientation

Desired Air Velocity (fpm)	Temperature Rise in Cage (°F)	Ventilation Rate (cfm)
20	8.41	0.06
30	8.92	0.05
40	9.08	0.07

Vertical Cage Orientation

Desired Air Velocity (fpm)	Temperature Rise in Cage (°F)	Ventilation Rate (cfm)
20	3.91	0.08
30	5.52	0.09
40	6.89	0.11

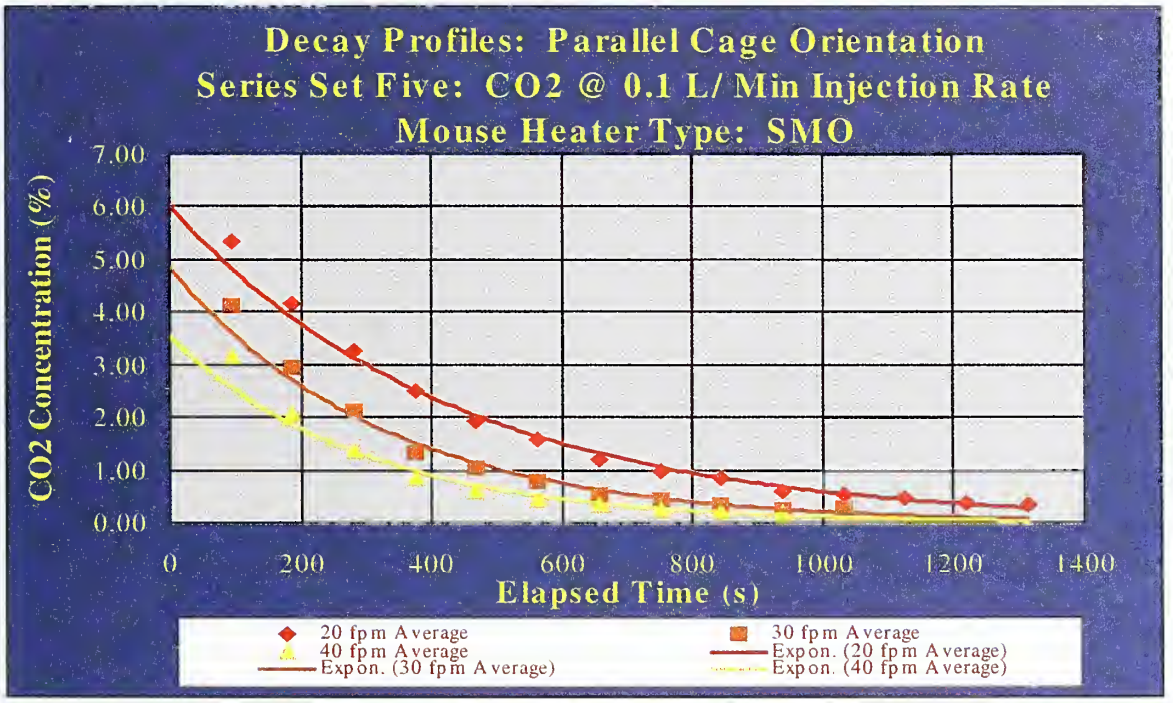


2.2.6 *Series Set Five - Decay Results*

Parallel Cage Orientation

Summary

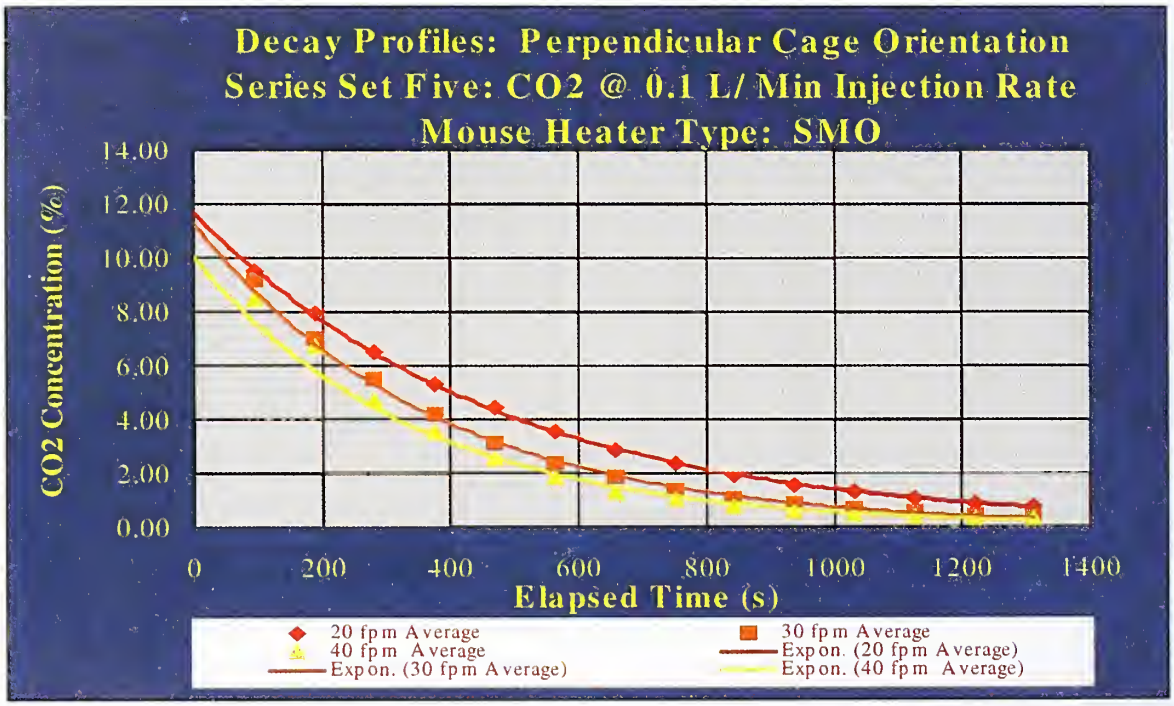
Tunnel Velocity (fpm)	Time to Decay (min)		
	90 percent	95 percent	99 percent
Keller,White, Synder and Lang Paper @ 16 fpm (May 1989)	18.27	23.77	36.54
20	16.69	21.27	33.37
30	12.38	16.11	24.76
40	11.29	14.68	22.57



Perpendicular Cage Orientation

Summary

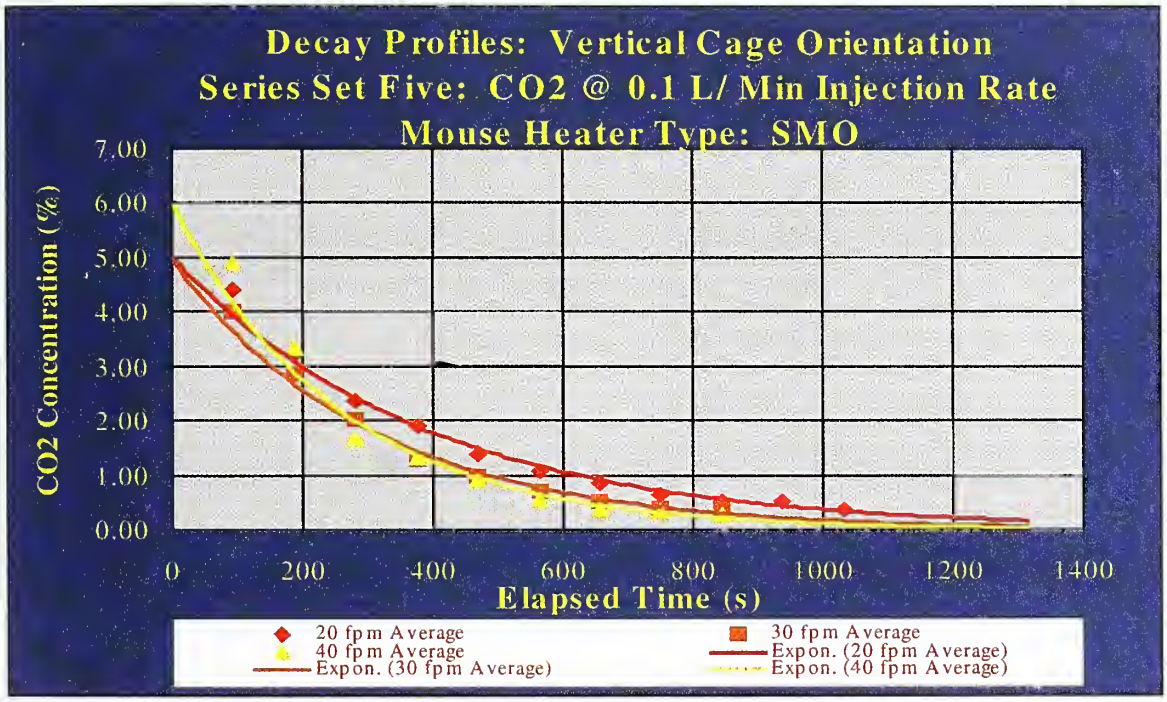
Tunnel Velocity (fpm)	Time to Decay (min)		
	90 percent	95 percent	99 percent
20	18.27	23.77	36.54
30	14.21	18.49	28.43
40	13.23	17.22	26.47



Vertical Cage Orientation

Summary

Tunnel Velocity (fpm)	Time to Decay (min)		
	90 percent	95 percent	99 percent
20	14.26	19.20	29.52
30	11.63	15.13	23.26
40	9.84	12.81	19.68



2.2.7 Series Set Six - Sealed Cage Lips

Parallel Cage Orientation: Heater On

Desired Air Velocity (fpm)	Temperature Rise in Cage (°F)		Ventilation Rate (cfm)	
	DMH	SMO	DMH	SMO
20	5.34	8.85	0.07	0.04
40	4.47	6.23	0.07	0.04

Parallel Cage Orientation: Heater Off

Desired Air Velocity (fpm)	Temperature Rise in Cage (°F)	Ventilation Rate (cfm)
20	2.09	0.04
40	2.96	0.05

Perpendicular Cage Orientation: Heater On

Desired Air Velocity (fpm)	Temperature Rise in Cage (°F)		Ventilation Rate (cfm)	
	DMH	SMO	DMH	SMO
20	5.68	8.45	0.05	0.05
40	5.08	8.96	0.06	0.05

Perpendicular Cage Orientation: Heater Off

Desired Air Velocity (fpm)	Temperature Rise in Cage (°F)	Ventilation Rate (cfm)
20	4.04	0.04
40	2.76	0.04

2.2.8 Series Set Seven - Sealed Filter Top

Parallel Cage Orientation: Heater On

Desired Air Velocity (fpm)	Temperature Rise in Cage (°F)		Ventilation Rate (cfm)	
	DMH	SMO	DMH	SMO
20	3.72	6.45	0.03	0.05
40	3.02	7.96	0.05	0.11

Parallel Cage Orientation: Heater Off

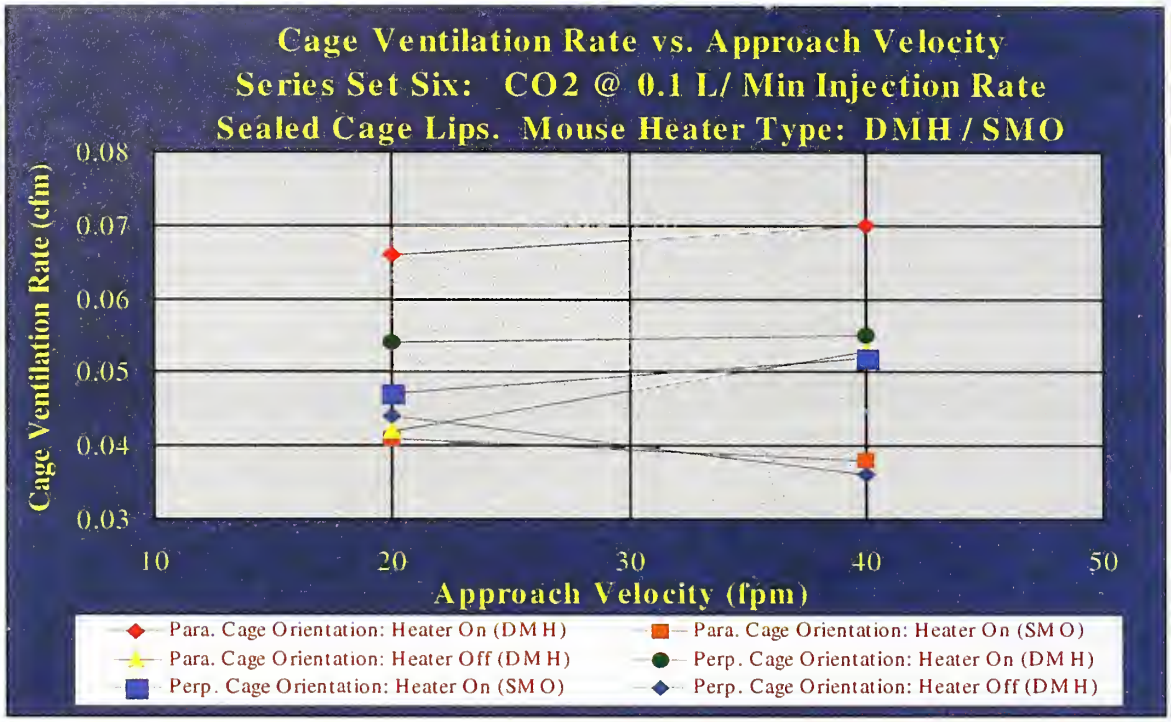
Desired Air Velocity (fpm)	Temperature Rise in Cage (°F)	Ventilation Rate (cfm)
20	6.45	0.04
40	7.96	0.05

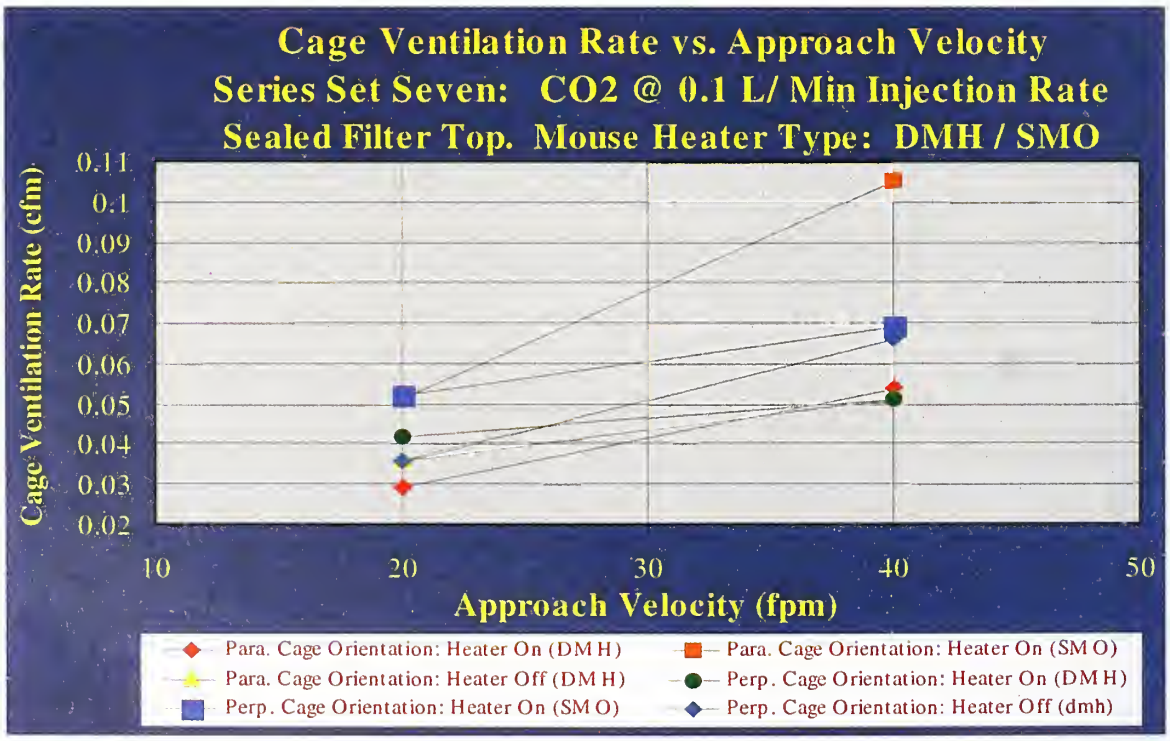
Perpendicular Cage Orientation: Heater On

Desired Air Velocity (fpm)	Temperature Rise in Cage (°F)		Ventilation Rate (cfm)	
	DMH	SMO	DMH	SMO
20	6.00	10.21	0.04	0.05
40	4.17	11.13	0.05	0.07

Perpendicular Cage Orientation: Heater Off

Desired Air Velocity (fpm)	Temperature Rise in Cage (°F)	Ventilation Rate (cfm)
20	10.21	0.04
40	11.13	0.07


Cage Ventilation Rate vs. Approach Velocity
Series Set Six: CO2 @ 0.1 L/ Min Injection Rate
Sealed Cage Lips. Mouse Heater Type: DMH / SMO
Cage Ventilation Rate (cfm)
0.08
0.07
0.06
0.05
0.04
0.03
10
20
30
40
50
Approach Velocity (fpm)
Para. Cage Orientation: Heater On (DMH)
Para. Cage Orientation: Heater On (SMO)
Para. Cage Orientation: Heater Off (DMH)
Perp. Cage Orientation: Heater On (DMH)
Perp. Cage Orientation: Heater On (SMO)
Perp. Cage Orientation: Heater Off (DMH)


Cage Ventilation Rate vs. Approach Velocity
Series Set Seven: CO2 @ 0.1 L/ Min Injection Rate
Sealed Filter Top. Mouse Heater Type: DMH / SMO
Cage Ventilation Rate (cfm)
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
10
20
30
40
50
Approach Velocity (fpm)
Para. Cage Orientation: Heater On (DMH)
Para. Cage Orientation: Heater On (SMO)
Para. Cage Orientation: Heater Off (DMH)
Perp. Cage Orientation: Heater On (DMH)
Perp. Cage Orientation: Heater On (SMO)
Perp. Cage Orientation: Heater Off (dmh)

2.2.9 Series Set Eight - Double Cage Scenarios

Parallel and Perpendicular Double Cage Scenarios (30 fpm Only): Heater On

Cage Orientation	Ventilation Rate (cfm)
Parallel	0.09
Perpendicular	0.08

2.3 Justification of Dimensions of Simulated Mouse Object

From Gordon, C.J. 1993. *Temperature Regulation in Laboratory Rodents*, page 57.

"...Because heat exchange between an animal and its environment occurs over its exposed surface area, expressing metabolic rate in terms of surface area is often preferred. Whereas body mass obviously is a simple parameter to measure, surface area must be estimated using a power relationship with certain assumptions:

$$SA = kW^{0.67}$$

where SA is surface area in square centimeters, W is the species weight in grams, and the constant k, termed the Meeb coefficient, is species-dependent, with a wide range of intraspecies values, ranging from 6.9 to 13.3 for mouse, 7.2 to 13.0 for rat, and 7.1 to 10.8 for guinea pig (Altman and Dittmer, 1962). These are incredibly wide variations, and they imply that a rodent of a given weight could have as much as double the surface area as another of the same weight, depending on which value of k is used in the calculation. Clearly, there has been considerable error in the determination of surface area. For rodents such as the mouse, rat, and guinea pig, a k value of 9.0 appears to be most accurate for calculating surface area (Herrington, 1940).

One problem with using surface area as a denominator in metabolic calculations is that the exposed area (i.e.. the skin where heat is transferred from the animal to the environment) can vary depending on the animal's behavior. For example, in a hot environment, rodents assume a sprawled posture to maximize surface area, whereas in the cold, the limbs are pulled close to the body to minimize the exposed surface area. Thus, the animal's thermoregulatory behavior affects heat loss per unit of exposed surface area, while heat loss per unit body mass remains relatively constant."

Using k=9, which is most accurate for rodents, the surface area will be:

$$SA = 9.0 \times (20)^{0.67} = 67cm^2$$
$$67cm^2 \times 0.155 = 10.38in^2$$

If use 7/8" diameter PVC pipe to represent mouse diameter, therefor two ends would be:

$$2 \times \left(\frac{0.875}{2}\right)^2 \times \pi = 1.2in^2$$
$$10.38 - 1.2 = 9.18in^2$$

9.18 in^2 is for pipe side area.

$$h\pi 0.875 = 9.18 \Rightarrow h = 3.34in$$

Therefore each mouse is made of a PVC pipe 7/8"diameter by 3 3/8" long.

3. CO_2, NH_3, H_2O AND HEAT GENERATION MEASUREMENTS AT LOW AND HIGH HUMIDITIES

Introduction to Direct and Indirect Calorimetry

3.1.1 The Definition and Measurement Techniques of Metabolic Rate

Calorimetry is used to estimate nutritional requirements of humans and farm livestock and to evaluate different foods. It is also a powerful research tool used to study fundamental nutritional and physiological life processes, and to evaluate stresses imposed by abnormal or severe environments. It is, lastly, used in clinics as a diagnostic tool for the investigation of metabolic disorders.

There are two principle types of animal calorimetry methods, direct and indirect. Direct calorimetery is the partitioned measurement of radiant, conductive, convective, and evaporative energy expenditure from animals. Indirect calorimetry determines energy expenditure from the chemical reactions that happen as oxygen is consumed and carbon dioxide is produced.

The metabolic rate in homeothermic animals is a function of ambient thermal conditions. Measurement of energy expenditure has been a powerful tool to study fundamental physiological processes, and to evaluate stresses imposed by abnormal or severe environments. Indirect calorimetry involves the measurement of respiratory gaseous exchange (O_2 consumption and CO_2 production) to calculate heat production. There are now numerous indirect calorimeters around the world (Nienaber et al. 1985; Meo 1989; Mathison et al. 1991), although there are only two known laboratories with convective calorimeters, which control air velocity as well as temperature. In comparative physiology, the metabolic rate of an animal is defined to be its rate of energy consumption, that is, the rate at which it converts chemical energy to heat and external work. One reason that the metabolic rate of an animal is significant is that the heat and external work exported from the animal reflect quantitatively the overall activity of its physiological machinery. Heat, in particular, is liberated by every process in the body that uses energy. Thus, the rate of heat production is a reflection of the sum total of the rates of all such processes. Heat is always the principal component of the metabolic rate. Therefore, for measurement of heat, the device used is called a calorimeter. Heat is one of the most conveniently handled forms of energy.

3.1.2 Direct Measurement of Metabolic Rate - Direct Calorimetry

An animal's metabolic rate can be measured in a device called a direct calorimeter, which by definition assays the rate at which heat is dissipated from the animal's body. Direct calorimetery is the partitioned measurement of radiant, conductive, convective, and evaporative energy expenditure from animals. The name calorimeter is derived from the calorie, a unit of measure for heat. Direct calorimeters are technically complex. They are designed to be especially accurate, sensitive, and versatile. Antoine Lavoisier used one in the first measurements of animal heat production in late 1700's. In his experiment, the animal was surrounded by an ice-filled

jacket. Ice melted by animal heat yielded water, which dripped out. A requirement for all direct calorimeters is that heat from the general environment must be excluded from the measurement of animal heat production. In Lavoisier's device, heat entering from the air surrounding the calorimeter was intercepted by a second ice-filled jacket that enclosed the first jacket that immediately surrounded the animal. Heat entering the animal area melted ice. Lavoisier was able to calculate the rate of heat output from the animal by collecting the water produced over measured periods of time, and by knowing the amount of heat required to melt each gram.

3.1.3 Indirect Measurement of Metabolic Rate - Indirect Calorimetry

Another method for measuring metabolic rates is an indirect method that has two advantages: relatively low cost and technical simplicity. An indirect calorimeter determines energy expenditure from the amounts of oxygen consumed and carbon dioxide produced in the chemical reactions that produce the energy expenditure. Heat production is based on using a mixed respiratory quotient (RQ). In indirect calorimetry, the gas analyzers take direct measurements of gas concentration in the calorimeter air stream. Thus the calculation of both oxygen consumption and carbon dioxide production can be determined by using the following relationships:

O_2 (L/min) = ΔO_2 percent x Flow Rate of Exhaust Air From Calorimeter (L/min) x {(Barometric Pressure (mmHg) x 273))/(760 x (273+C)}

CO_2 (L/min) = ΔCO_2 percent x Flow Rate of Exhaust Air From Calorimeter (L/min) x {(Barometric Pressure (mmHg) x 273))/(760 x (273+C)}

Where:

Δ O_2 (L/min) = percent O_2 entering calorimeter minus percent O_2 leaving calorimeter

Δ CO_2 (L/min) = percent CO_2 leaving calorimeter minus percent CO_2 entering calorimeter

C = Calorimeter inside temperature (°C)

The respiration quotient is defined as:

RQ = CO_2 (carbon dioxide production L/min)/ O_2 (oxygen consumption L/min)

Calculation of heat production is based on CO_2 and O_2 production and a fixed RQ value of 0.82. The heat production is calculated based on O_2 consumption calculated from a mixed RQ =0.82 which is for a caloric equivalent of 4.825 Kcal/LO_2. This is generally accurate within a 3 percent range regardless of actual RQ (R=0.7 with caloric equivalent of 4.686 Kcal/L O_2 and R= 1.0 with caloric equivalent of 5.047 Kcal/L O_2).

Heat production is calculated as follows:

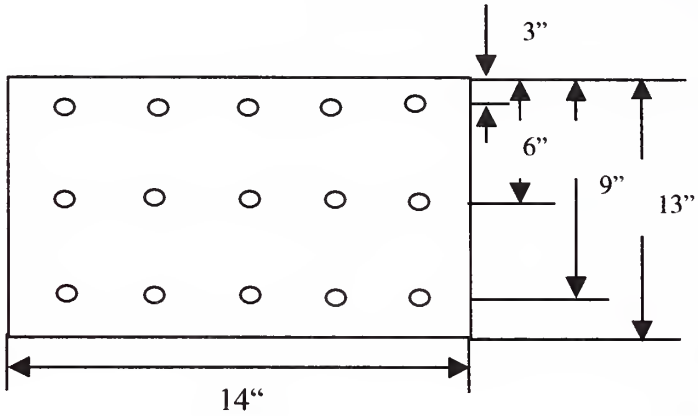
Hp (Kcal lkglhr)= O_2 consumption (L/min) x 60 x TE(KcalI/L O_2)

where:

TE = Thermal equivalent calories per liter of O_2 consumed (Value of 4.825 (Kcal/L O_2) is typically used)

3.2 Calibration Procedures

3.2.1 Calorimeter Approach Air Velocity Calibration: (Calibration Data Prior to Test 1)



Calorimeter #1							
	58	54	63	53	59		Av. =
Air velocity =	59	49	52	48	64	(fpm)	55 fpm
	62	51	52	44	62		
Voltage Regulated Setting = 10							

Calorimeter #2							
	72	48	50	57	66		Av. =
Air velocity =	68	51	47	56	63	(fpm)	58 fpm
	74	50	52	56	59		
Voltage Regulated Setting = 64							

Calorimeter #3							
	55	47	51	55	59		Av. =
Air velocity =	53	44	44	50	65	(fpm)	51 fpm
	58	39	38	43	58		
Voltage Regulated Setting = 61							

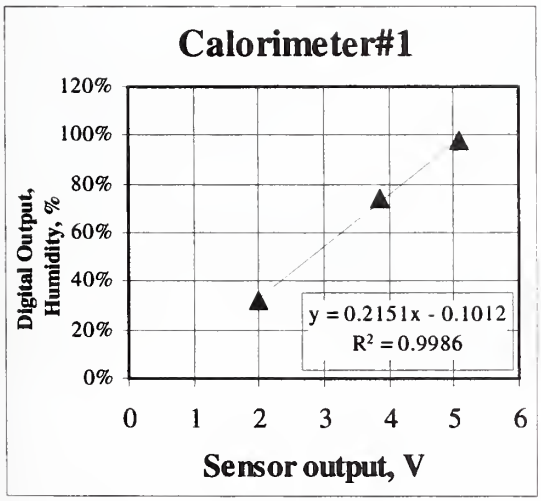
3.2.2 *Calorimeter Approach Air Velocity Calibration: (Calibration Data Prior to Test 2)*

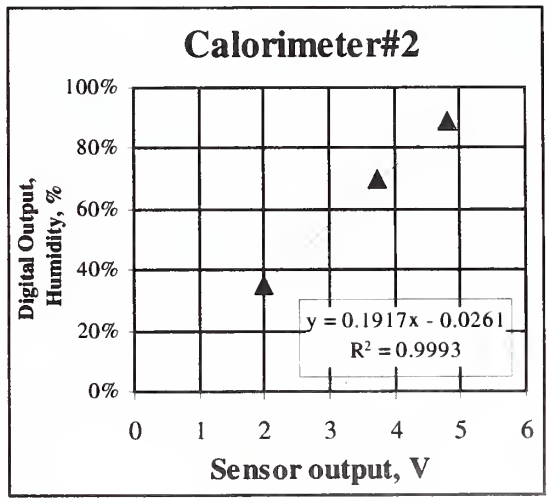
Calorimeter #1								
		69	48	50	47	56		Av. =
Air velocity =		55	44	47	51	51	(fpm)	51fpm
		64	48	47	45	46		
Voltage Regulated Setting = 106								

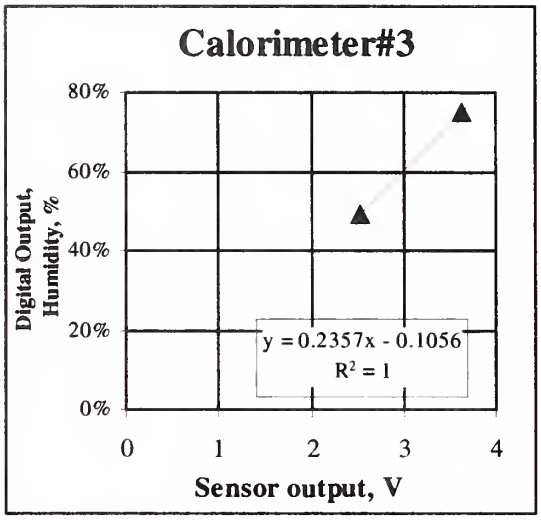
Calorimeter #2								
		67	52	53	54	65		Av. =
Air velocity =		65	43	40	58	62	(fpm)	54 fpm
		71	43	40	54	47		
Voltage Regulated Setting = 62								

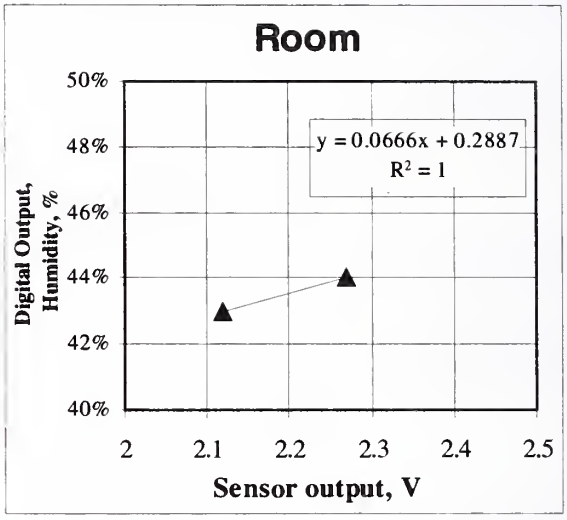
Calorimeter #3								
		63	45	40	49	64		Av. =
Air velocity =		51	44	39	51	59	(fpm)	50 fpm
		60	41	39	45	55		
Voltage Regulated Setting = 61								

3.2.3 *Calibration of Humidity Sensors: (Calibration Data Prior to Test 1)*

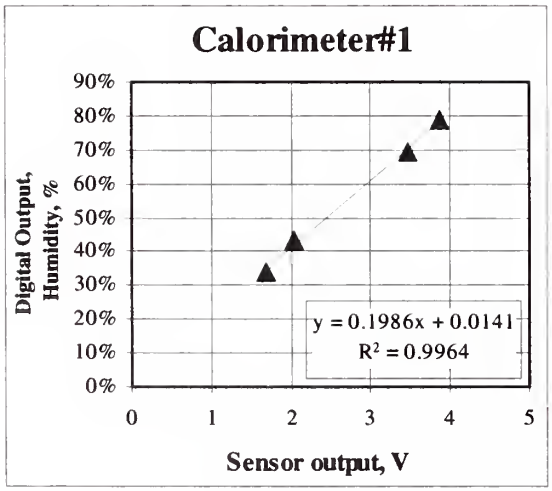


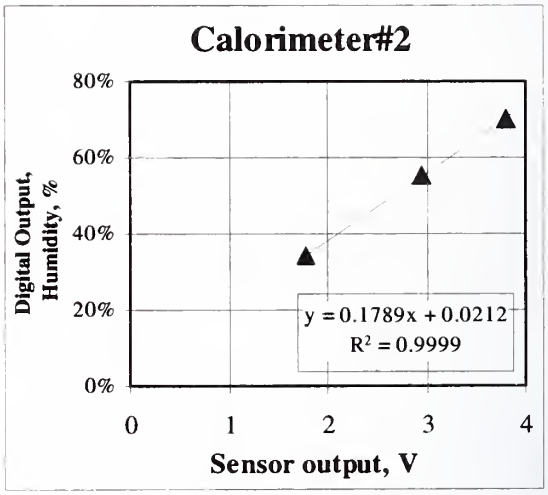


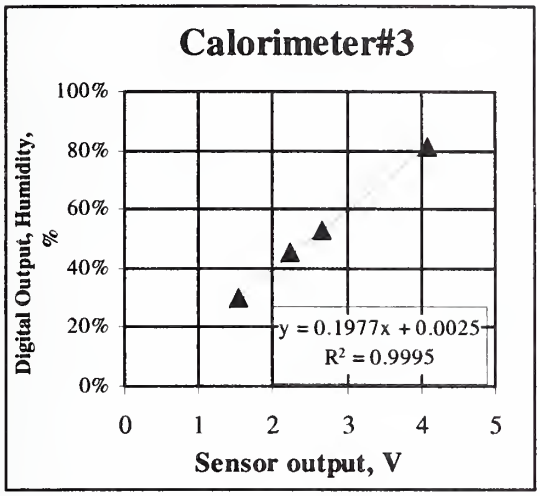


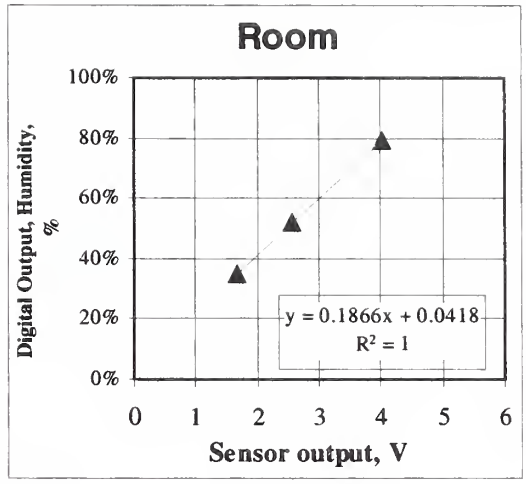


Calibration of Humidity Sensors: (Calibration Data Prior to Test 2)

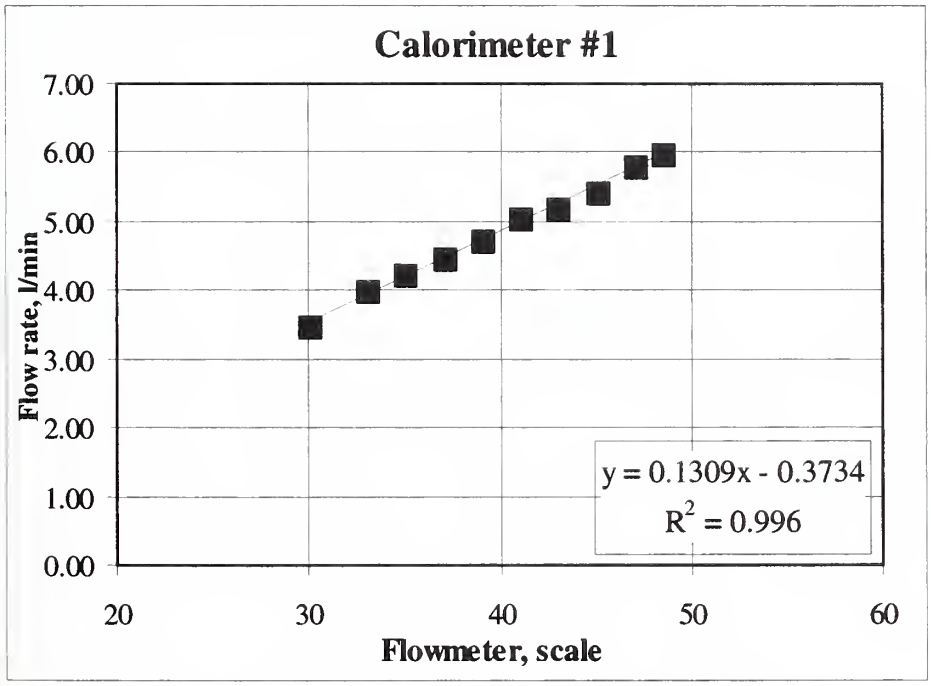


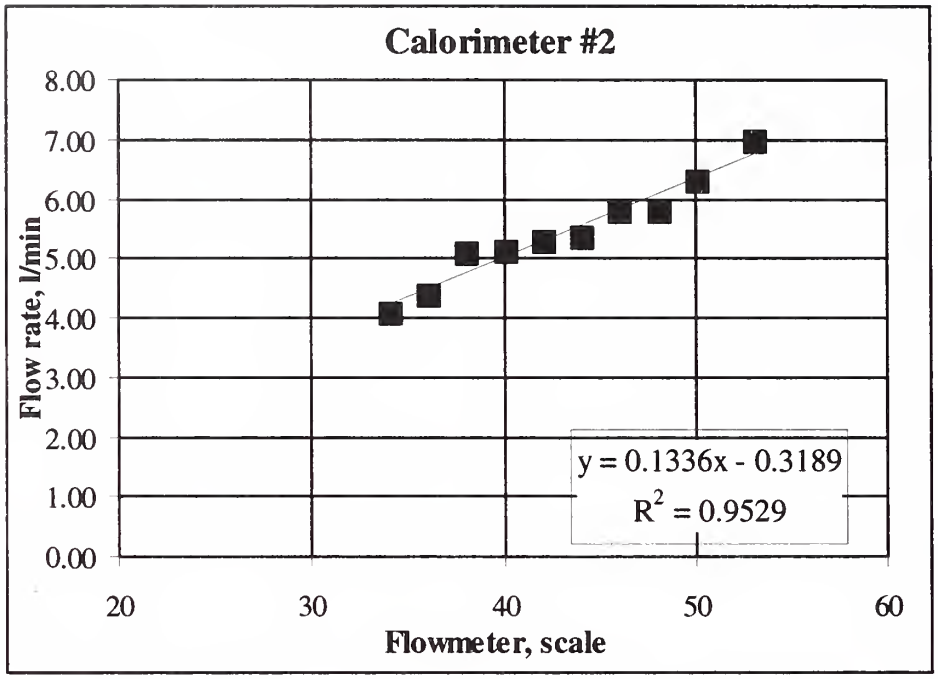


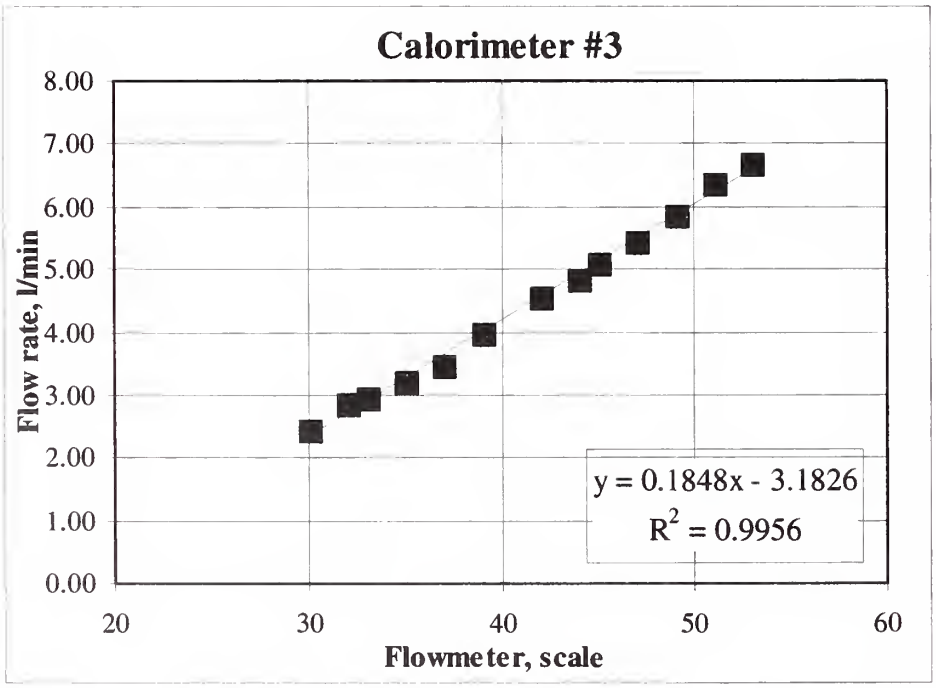




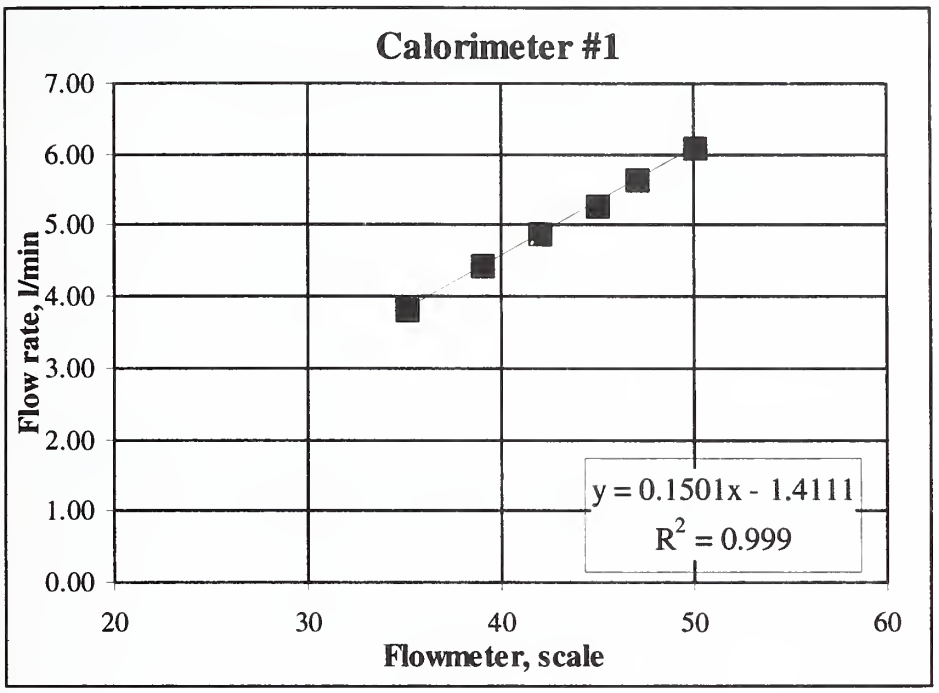
3.2.5 Calibration of Calorimeter Fresh Airflow Meter (Calibration Data Prior to Test 1)

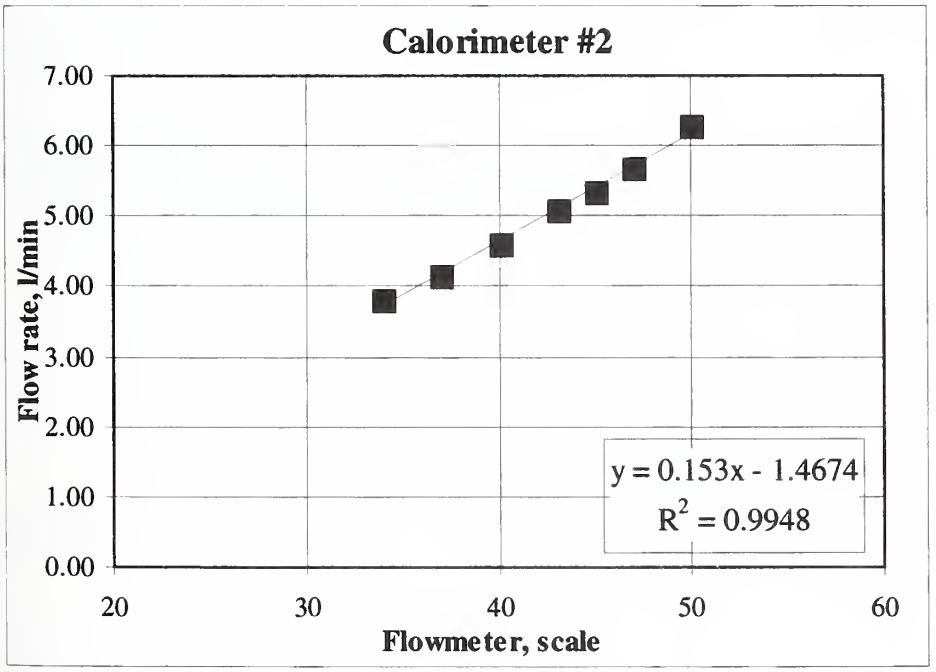


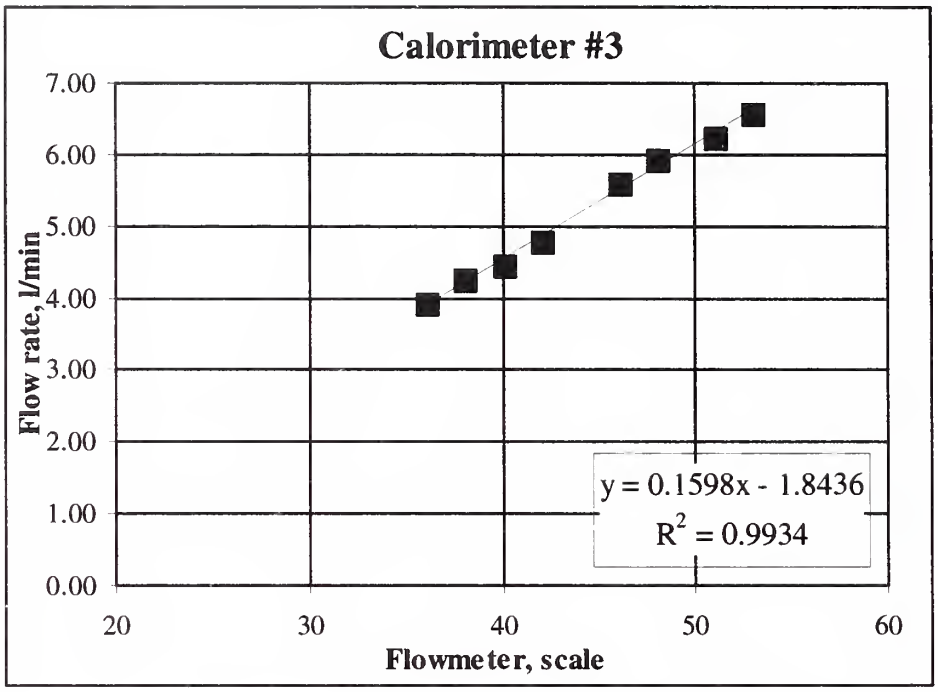

Calorimeter #2
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Flow rate, l/min
20
30
40
50
60
Flowmeter, scale
y = 0.1336x - 0.3189
R2 = 0.9529


Calorimeter #3
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Flow rate, l/min
20
30
40
50
60
Flowmeter, scale
y = 0.1848x - 3.1826
R2 = 0.9956

3.2.6 Calibration of Calorimeter Fresh Airflow Meter (Calibration Data Prior to Test 2)






Calorimeter #3
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
Flow rate, l/min
20
30
40
50
60
Flowmeter, scale
y = 0.1598x - 1.8436
R2 = 0.9934

3.2.7 *Calorimeter CO_2 and O_2 Recovery Calibration: (Calibration Data Prior to Test 1)*

Calorimeter #1

Time (min)	CO_2 (percent)	Room CO_2 (percent)	Gen. CO_2[a] (L/min)	O_2 (percent)	Room O_2 (percent)	Con O_2[b] (L/min)	Ethanol wt[c] (g)
0	1.00	0.10	0.0497	19.2	20.5	0.072	156.64
10	1.00	0.10	0.0497	19.2	20.5	0.072	156.17
20	1.00	0.10	0.0497	19.2	20.5	0.072	155.67
30	1.00	0.10	0.0497	19.2	20.5	0.072	155.20
40	1.00	0.10	0.0497	19.2	20.5	0.072	154.72
50	1.01	0.10	0.0502	19.1	20.5	0.077	154.27
60	1.01	0.10	0.0502	19.1	20.5	0.077	153.72

Flow rate=5.52 l/min

Calorimeter #2

Time (min)	CO_2 (percent)	Room CO_2 (percent)	Gen. CO_2[a] (L/min)	O_2 (percent)	Room O_2 (percent)	Con O_2[b] (L/min)	Ethanol wt[c] (g)
0	1.13	0.11	0.0563	19.0	20.4	0.0773	167.35
10	1.13	0.11	0.0563	19.0	20.5	0.0828	166.84
20	1.14	0.11	0.0569	19.0	20.5	0.0828	166.32
30	1.14	0.11	0.0569	19.0	20.5	0.0828	165.82
40	1.13	0.11	0.0563	19.0	20.5	0.0828	165.32
50	1.13	0.11	0.0563	19.1	20.5	0.0773	164.82
60	1.14	0.11	0.0569	19.0	20.6	0.0883	164.32
70	1.14	0.11	0.0569	19.1	20.6	0.0828	163.81

Flow rate=5.52 l/min

Calorimeter #3

Time (min)	CO_2 (percent)	Room CO_2 (percent)	Gen. CO_2[a] (L/min)	O_2 (percent)	Room O_2 (percent)	Con O_2[b] (L/min)	Ethanol wt[c] (g)
0	1.28	0.07	0.0668	18.9	20.6	0.0938	167.65
10	1.29	0.07	0.0673	18.9	20.6	0.0938	166.97
20	1.29	0.07	0.0673	18.9	20.6	0.0938	166.30
30	1.29	0.07	0.0673	18.9	20.6	0.0938	165.62
40	1.29	0.07	0.0673	18.9	20.5	0.0883	164.95
50	1.29	0.07	0.0673	18.9	20.5	0.0883	164.29
60	1.29	0.07	0.0673	18.9	20.5	0.0883	163.58
70	1.29	0.07	0.0673	19.0	20.5	0.0828	162.90

Flow rate=5.52 l/min

Calorimeter #1

Time (min)	Different wt[d] (g)	P CO_2[e] (L/min)	P O_2[f] (L/min)	RQ[g]	O_2 Recovery Ratio (percent)	CO_2 Recovery Ratio (percent)
0				0.69		
10	0.47	0.0457	0.0686	0.69	104.61	108.63
20	0.50	0.0487	0.0730	0.69	98.33	102.11
30	0.47	0.0457	0.0686	0.69	104.61	108.63
40	0.48	0.0467	0.0701	0.69	102.43	106.37
50	0.45	0.0438	0.0657	0.65	117.66	114.72
60	0.55	0.0535	0.0803	0.65	96.27	93.86

Calorimeter #2

Time (min)	Different wt[d] (g)	P CO_2[e] (L/min)	P O_2[f] (L/min)	RQ[g]	O_2 Recovery Ratio (percent)	CO_2 Recovery Ratio (percent)
0				0.73		
10	0.51	0.0496	0.0744	0.68	111.23	113.46
20	0.52	0.0506	0.0759	0.69	109.09	112.37
30	0.50	0.0487	0.0730	0.69	113.46	116.86
40	0.50	0.0487	0.0730	0.68	113.46	115.73
50	0.50	0.0487	0.0730	0.73	105.89	115.73
60	0.50	0.0487	0.0730	0.64	121.02	116.86
70	0.51	0.0496	0.0744	0.69	111.23	114.57

Calorimeter #3

Time (min)	Different wt[d] (g)	P CO_2[e] (L/min)	P O_2[f] (L/min)	RQ[g]	O_2 Recovery Ratio (percent)	CO_2 Recovery Ratio (percent)
0				0.71		
10	0.68	0.0662	0.0993	0.72	94.55	101.78
20	0.67	0.0652	0.0978	0.72	95.96	103.30
30	0.68	0.0662	0.0993	0.72	94.55	101.78
40	0.67	0.0652	0.0978	0.76	90.31	103.30
50	0.66	0.0642	0.0963	0.76	91.68	104.86
60	0.71	0.0691	0.1036	0.76	85.23	97.48
70	0.68	0.0662	0.0993	0.81	83.42	101.78

a. CO_2 generation rate based on CO_2 concentration and air exchange flow rate.
b. O_2 generation rate based on O_2 concentration and air exchange flow rate.
c. Weight of ethanol for every 10 minutes.
d. Different weight of ethanol based on 10 minutes /production of CO_2 due to burning ethanol.
e. CO_2 generation rate based on burning ethanol.
f. O_2 generation rate based on burning ethanol.
g. Respiration quotient.

3.2.8 Calorimeter CO_2 and O_2 Recovery Calibration: (Calibration Data Prior to Test 2)

Calorimeter #1

Time (min)	CO_2 (percent)	Room CO_2 (percent)	Gen. CO_2[a] (L/min)	O_2 (percent)	Room O_2 (percent)	Con O_2[b] (L/min)	Ethanol wt[c] (g)
0	1.53	0.06	0.0697	18.8	20.7	0.0901	153.83
10	1.53	0.06	0.0697	18.6	20.6	0.0949	153.15
20	1.53	0.06	0.0697	18.6	20.6	0.0949	152.49
30	1.53	0.06	0.0697	18.6	20.7	0.0996	151.83
40	1.53	0.05	0.0702	18.6	20.7	0.0996	151.16
50	1.54	0.05	0.0707	18.5	20.6	0.0996	150.49
60	1.54	0.05	0.0707	18.6	20.6	0.0949	149.82
70	1.54	0.05	0.0707	18.6	20.7	0.0996	149.15

Flow rate = 4.743 l/min

Calorimeter #2

Time (min)	CO_2 (percent)	Room CO_2 (percent)	Gen. CO_2[a] (L/min)	O_2 (percent)	Room O_2 (percent)	Con O_2[b] (L/min)	Ethanol wt[c] (g)
0	1.53	0.05	0.0740	18.6	20.7	0.1050	163.95
10	1.53	0.05	0.0740	18.6	20.7	0.1050	163.26
20	1.53	0.05	0.0740	18.6	20.7	0.1050	162.58
30	1.53	0.05	0.0740	18.6	20.8	0.1100	161.89
40	1.54	0.05	0.0745	18.6	20.8	0.1100	161.18
50	1.54	0.05	0.0745	18.6	20.8	0.1100	160.51
60	1.54	0.05	0.0745	18.6	20.8	0.1100	159.81
70	1.54	0.05	0.0745	18.6	20.8	0.1100	159.12

Flow rate = 5 l/min

Calorimeter #3

Time (min)	CO_2 (percent)	Room CO_2 (percent)	Gen. CO_2[a] (L/min)	O_2 (percent)	Room O_2 (percent)	Con O_2[b] (L/min)	Ethanol wt[c] (g)
0	1.57	0.05	0.0608	18.7	20.6	0.0760	151.03
10	1.57	0.04	0.0612	18.6	20.6	0.0800	150.41
20	1.57	0.04	0.0612	18.7	20.6	0.0760	149.82
30	1.57	0.04	0.0612	18.6	20.7	0.0840	149.21
40	1.57	0.04	0.0612	18.7	20.6	0.0760	148.62
50	1.58	0.03	0.0620	18.6	20.8	0.0880	148.03
60	1.58	0.03	0.0620	18.6	20.8	0.0880	147.43
70	1.58	0.03	0.0620	18.6	20.8	0.0880	146.83

Flow rate = 4 l/min

Calorimeter #1

Time (min)	Different wt[d] (g)	P CO_2[e] (L/min)	P O_2[f] (L/min)	RQ[g]	O_2 Recovery Ratio (percent)	CO_2 Recovery Ratio (percent)
10	0.68	0.0662	0.0993	0.74	95.58	105.37
20	0.66	0.0642	0.0963	0.74	98.47	108.56
30	0.66	0.0642	0.0963	0.70	103.40	108.56
40	0.67	0.0652	0.0978	0.70	101.85	107.67
50	0.67	0.0652	0.0978	0.71	101.85	108.40
60	0.67	0.0652	0.0978	0.75	97.00	108.40
70	0.67	0.0652	0.0978	0.71	101.85	108.40

Calorimeter #2

Time (min)	Different wt[d] (g)	P CO_2[e] (L/min)	P O_2[f] (L/min)	RQ[g]	O_2 Recovery Ratio (percent)	CO_2 Recovery Ratio (percent)
0						
10	0.69	0.0671	0.1007	0.70	104.26	110.22
20	0.68	0.0662	0.0993	0.70	105.79	111.84
30	0.69	0.0671	0.1007	0.70	109.22	110.22
40	0.71	0.0691	0.1036	0.67	106.15	107.84
50	0.67	0.0652	0.0978	0.68	112.48	114.27
60	0.70	0.0681	0.1022	0.68	107.66	109.38
70	0.69	0.0671	0.1007	0.68	109.22	110.96

Calorimeter #3

Time (min)	Different wt[d] (g)	P CO_2[e] (L/min)	P O_2[f] (L/min)	RQ[g]	O_2 Recovery Ratio (percent)	CO_2 Recovery Ratio (percent)
0				0.80		
10	0.62	0.0603	0.0905	0.77	88.40	101.44
20	0.59	0.0574	0.0861	0.81	88.25	106.60
30	0.61	0.0594	0.0890	0.73	94.35	103.11
40	0.59	0.0574	0.0861	0.81	88.25	106.60
50	0.59	0.0574	0.0861	0.70	102.19	107.99
60	0.60	0.0584	0.0876	0.70	100.49	106.19
70	0.60	0.0584	0.0876	0.70	100.49	106.19

a. CO_2 generation rate based on CO_2 concentration and air exchange flow rate.
b. O_2 generation rate based on O_2 concentration and air exchange flow rate.
c. Weight of ethanol for every 10 minutes.
d. Different weight of ethanol based on 10 minutes /production of CO_2 due to burning ethanol.
e. CO_2 generation rate based on burning ethanol.
f. O_2 generation rate based on burning ethanol.
g. Respiration quotient.

3.2.9 Cage/Calorimeter Assignment for Test 1

Day	Calorimeter	Relative Humidity (percent)	Cages	Date
1	1	35	1,2,3,4,	10/18/97
	2	75	5,6,7,8,	
	3	35	9,10,11,12,	
2	1	75	5,6,7,8,	10/19/97
	2	35	9,10,11,12,	
	3	35	1,2,3,4,	
3	1	35	9,10,11,12,	10/20/97
	2	35	1,2,3,4,	
	3	75	5,6,7,8,	
4	1	35	1,2,3,4,	10/21/97
	2	75	5,6,7,8,	
	3	35	9,10,11,12,	
5	1	75	5,6,7,8,	10/22/97
	2	35	9,10,11,12,	
	3	35	1,2,3,4,	
6	1	35	9,10,11,12,	10/23/97
	2	35	1,2,3,4,	
	3	75	5,6,7,8,	
7	1	35	1,2,3,4,	10/24/97
	2	75	5,6,7,8,	
	3	35	9,10,11,12,	
8	1	75	5,6,7,8,	10/25/97
	2	35	9,10,11,12,	
	3	35	1,2,3,4,	
9	1	35	9,10,11,12,	10/26/97
	2	35	1,2,3,4,	
	3	75	5,6,7,8,	
10	1	35	1,2,3,4,	10/27/97
	2	75	5,6,7,8,	
	3	35	9,10,11,12,	

3.2.10 Cage/Calorimeter Assignment for Test 2

Day	Calorimeter	Relative Humidity (percent)	Cages	Date
1	1	35	1,2,3,4,	12/13/97
	2	75	5,6,7,8,	
	3	75	9,10,11,12,	
2	1	75	5,6,7,8,	12/14/97
	2	75	9,10,11,12,	
	3	35	1,2,3,4,	
3	1	75	9,10,11,12,	12/15/97
	2	35	1,2,3,4,	
	3	75	5,6,7,8,	
4	1	35	1,2,3,4,	12/16/97
	2	75	5,6,7,8,	
	3	75	9,10,11,12,	
5	1	75	5,6,7,8,	12/17/97
	2	75	9,10,11,12,	
	3	35	1,2,3,4,	
6	1	75	9,10,11,12,	12/18/97
	2	35	1,2,3,4,	
	3	75	5,6,7,8,	
7	1	35	1,2,3,4,	12/19/97
	2	75	5,6,7,8,	
	3	75	9,10,11,12,	
8	1	75	5,6,7,8,	12/20/97
	2	75	9,10,11,12,	
	3	35	1,2,3,4,	
9	1	75	9,10,11,12,	12/21/97
	2	35	1,2,3,4,	
	3	75	5,6,7,8,	
10	1	35	1,2,3,4,	12/22/97
	2	75	5,6,7,8,	
	3	75	9,10,11,12,	

3.3 Measurement Procedures

3.3.1 Operating Procedure for Starting Calorimeters

Make sure the room furnace or air conditioner is working.

Turn on environmental chamber (EC) #1 power switch on front outside panel and make sure the right knob is rotated to the correct temperature, around 70 °F.

Turn on CO_2 and O_2 analyzers. Use the proper procedure.

Turn on EC #2 power switch on front panel outside the chamber and flip the switch up on the box at left-hand side of front panel. Check thermostat inside the chamber so it is around 68 °F.

Turn on the duct fans for the calorimeter temperature control systems.

Turn on the calorimeter temperature control panels inside EC #1. Adjust it to the correct temperature if this has not already been done.

Turn on the calorimeter recirculating fans with the control inside EC #1.

Turn on the sample pumps outside EC #1.

Turn on the solenoid valve control system.

To shut off calorimeters, reverse this order.

3.3.2 Operating Procedure for Using the CO_2 Analyzer

1. Turning on:

Press in the top button on the left of the analyzer.

Wait one minute.

Press in the bottom button.

Wait 30 minutes for the machine to warm up.

2. Adjust the lower concentration standard gas using the zero dial to the concentration on the tank. The flow rate from the tank should read 2.5L/min on the gauge.

3. Adjust the higher concentration standard gas using the gain dial to the concentration on the tank the flow rate from the tank should read 2.5L/min on the gauge.

4. Move the intake tube from the standard gas tube to the sample tube.

5. Record values.

6. Do not turn the machine off until the end of the day because it takes 30 minutes to warm it up.

Turning off:

Press the bottom button on the left of the analyzer.

Wait one minute.

Press the top button on the left of the analyzer.

3.3.3 Operating Procedures for Relative Humidity Measurement

Turn computer on and do not touch the keyboard until you get the C prompt (C:\>).

At the C prompt (C:\>), type "viewdac" and then hit the enter key.

At the viewdac copyright window, click "START."

At the menu bar at the top of the screen, click "File." Then click "Open" and then click "Sequence."

You should see a window in the center of the screen that says "File open for sequence."

Go down the list of files until you see the one that says "Humidical.seq." Click on it once and then click "OK."

At the "Humidical.seq" window, highlight task of "ASCII write," change name of ASCII file by clicking the "edit" button on the "Humidical.seq" window. Name the file: morningdate or afternoondate.

Click "Start" button on the "Humidical.seq" window to run the program.
When finished measuring the task, click once on the "Stop" button on the "Humidical.seq" window.

At the menu bar, click on "System" and then click on "Shell DOS." At the C prompt, copy the ASCII file onto a floppy disk.

At the menu bar at the top of the screen, click on "File" and then click on "Close." On the menu bar, click on "System" and then click on "Bye." You should be back at the C prompt.

Shut off the CPU and monitor.

3.3.4 Operating Procedures for Humidification System

Every morning:

Disconnect the graduated cylinder from its tubing (directly below the needle valve at the bottom of the fitting that connects the tubing to the solenoid). Some water may drip out of the needle valve.

Take the graduated cylinder to the sink in the main lab.

Open the needle valve all the way and fill the graduated cylinder with water. Allow the cylinder to drain and repeat until water flows freely through the needle valve.

Close the needle valve all the way and fill the graduated cylinder with water to check for leaks. If there is a leak, patch it with the sealer.

Open the valve until there is a very slow drip, about one drip every five seconds.

Empty the cylinder and refill to 30 mL. Check if there is a slow drip with the cylinder filled to 30 mL. If there is, fill the cylinder to about 90mL. If there is not, open the valve until it starts dripping slowly. Refill the cylinder and repeat steps five and six until a steady flow is achieved at both 30 and 90 mL.

Reattach the cylinder to the calorimeter. Repeat steps one through seven for all three calorimeters.

Turn the solenoids on and off 10 times. Turn the solenoids on and be sure that water is flowing out of the needle valves. If no water is flowing out, turn the solenoids on and off 10 more times. If water still does not flow, open the needle valve four turns. If water still does not flow out, seek assistance.

Record the current water volume within the cylinders. Make sure the cylinder is almost vertical.

Record the water volume at the end of each run.

3.3.5 Operating Procedures for Baking Drierite

1. Set oven to about 425 °F. Match up black lines under the broken knob.

2. Place drierite in large pans to a depth of around ½ inch and place pans on the three shelves in oven.

3. Bake for 1.5 hours.

4. Remove and dump into shoebox cage.

5. Refill pans and place in oven.

6. Immediately fill jars from the shoebox cage and put on lids snugly, but not tightly. Leave jars on floor to cool.

7. When done, turn oven knob counterclockwise to shut off.

3.3.6 Operating Procedures for NH_3, CO_2, and O_2 Measurements

There are three calorimeters (#1, #2, and #3) running at the same time. They all run at 24 ± 1.5 °C. The humidities in the three calorimeters are 35 percent, 35 percent, and 75 percent, for the first test and 75 percent, 75 percent, and 35 percent for the second test. The fresh airflow rate for the calorimeter is 5L/min. This is increased in the 8th, 9th, and 10th test day. The air recirculation system moves air past the cages at 0.25m/s. NH_3 and CO_2 levels will be monitored to ensure that the CO_2 concentration does not exceed 6,000 ppm and the NH_3 levels does not exceed 100 ppm for long periods. The calorimeter static pressure is kept negative. The samples are taken when the ammonia concentrations inside calorimeters reach a stable state.

Time a.m.	Actions
7:00	Turn on all the calorimeter environmental control systems including CO_2, O_2 analyzer (see procedure for start calorimeter and CO_2 analyzer).
	Weigh the new recycling drierite, new fresh air drierite and new humidification water.
	Weigh and record the mouse weight, water, feed, and litter. Add water and feed to the mouse cages.
	Reweigh, record the water, and feed.
7:40	Put the mice into the calorimeter (four cages per calorimeter).
	Turn on recycling pumps in 35 percent calorimeter for one hour.

Turn on humidification solenoid if 75 percent calorimeter has a lower humidity and turn on dehumidification pump if it has higher humidity.

Check fresh airflow going into drierite with the bubble flow meter.

Put old drierite into oven and bake (see detailed procedures).

8:40 Turn off the dehumidifier and record the humidity values of each calorimeter.

10:30 Calibrate the PhD meter with NH_3 by using a standard ammonia gas (52.7 ppm) and the fresh air.

Calibrate CO_2 and O_2 analyzer by using two standard gases (CO_2 0.55 percent, O_2 17.5 percent and CO_2 1.58 percent, O_2 18.9 percent).

Record the atmospheric pressure from mercurial barometer (Fortin Type, model 469).

10:40 Record the CO_2, O_2, RH (see other detailed procedures), temperature, and airflow. Measure NH_3 of each calorimeter and room using PhD meter and calorimetric tube, respectively.

11:20 Start the second sample period, in which NH_3 is measured only using PhD.

p.m.

12:00 Start the third sample period, which is same as second one.

12:30 Turn off the white light. Start the dehumidification system in the 35 percent calorimeter.

1:30 Turn off the dehumidification system.

3:00 Calibrate the PhD meter with standard NH_3 gas (52.7 ppm) and fresh air.

Calibrate CO_2 and O_2 analyzer.

Record the atmospheric pressure.

3:15 Record the CO_2, O_2, RH, temperature, and airflow for all three calorimeters.

Measure NH_3 using PhD meter and calorimetric tube.

4:00 Start the second sample period of the afternoon, in which NH_3 is measured only with PhD meter.

4:40 Start the third sample period, which is the same as the second one.

5:20 Put the mice back into the environmental chamber.

Weigh drierite and humidification water.

Turn off all the calorimeter environmental control systems (including CO_2, O_2 analyzer).

The test period is 10 days. Every day the same procedures will be repeated, except on the 11th day when we weigh the mice, water, and food, but do not add additional water and food.

3.4 Experimental Data

3.4.1 Tabulated Data

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3.4.1.1 Raw Data Test 1

Date: OCT 18,1997 **Day**: 1

Barometric pressure: 30.22 (in) **Desired temperature:** 24+-1.5 °C

Desired airflow: 5 (l/min)

Cage: 1,2,3,4					Calorimeter – 1 (desired RH 30-35 percent)			
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp (°C)	Actual RH (percent)
1	19.9	0.72	-1	41	4.99	69.20	20.67	71.69
2	20.1	0.75	0	41	4.99	70.40	21.33	74.48
3	19.9	0.76	0	40	4.86	70.60	21.44	75.00
Average	20.0	0.74	0	41	4.95	70.10	21.15	73.72
4	20.0	0.76	6	42	5.12	70.90	21.61	71.00
5	19.9	0.76	8	43	5.26	70.80	21.56	71.00
6	20.0	0.76	10	42	5.12	69.80	21.00	72.00
Average	20.0	0.76	8	42	5.20	70.50	21.40	71.33

Mice weight=401.6 (g). Thermocouple of Calorimeter-1 has problem. Actual temperature is not right.

Cage: 5,6,7,8					Calorimeter – 2 (desired RH 75-80 percent)			
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp (°C)	Actual RH (percent)
1	19.9	0.67	-1	39	4.89	74.40	23.56	86.30
2	20.0	0.63	2	37	4.62	73.90	23.28	87.43
3	20.1	0.63	0	39	4.89	73.70	23.17	86.70
Average	20.0	0.64	0	38	4.80	74.00	23.33	86.81
4	20.0	0.68	6	31	3.82	74.50	23.61	69.00
5	20.0	0.69	7	42	5.29	74.30	23.50	70.00
6	20.1	0.67	9	41	5.16	74.00	23.33	70.00
Average	20.0	0.68	7	38	4.80	74.30	23.50	69.67

Mice weight=409.8 (g)

Cage: 9,10,11,12					Calorimeter – 3 (desired RH 30-35 percent)			
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp (°C)	Actual RH (percent)
1	19.9	0.73	-1	50	6.06	73.30	22.94	72.59
2	20.0	0.61	1	50	6.06	73.80	23.22	72.50
3	20.1	0.61	0	50	6.06	73.40	23.00	71.67
Average	20.0	0.65	0	50	6.06	73.50	23.06	72.25
4	20.1	0.73	6	53	6.61	74.40	23.56	67.00
5	20.2	0.72	9	52	6.43	74.30	23.50	67.00
6	20.0	0.72	9	53	6.61	74.00	23.33	70.00
Average	20.1	0.72	8	53	6.60	74.20	23.50	68.00

Mice weight=421 (g)

Room (desired RH 35-40percent)								
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.5	0.06	0	-	-	66.00	18.89	34.10
2	20.7	0.06	2	-	-	66.00	18.89	36.47
3	20.7	0.06	-1	-	-	66.70	19.28	-
Average	20.6	0.06	0			66.23	19.02	35.29
4	20.7	0.06	8	-	-	67.20	19.56	38.00
5	20.6	0.06	7	-	-	67.10	19.50	37.00
6	20.7	0.06	11	-	-	67.00	19.44	38.00
Average	20.7	0.06	9			67.10	19.50	37.67

Date: OCT 19,1997 **Day:** 2
Barometric pressure: 30.02 (in) **Desired temperature:** 24+-1.5 °C
Desired airflow: 5 (l/min)

Cage: 5,6,7,8				Calorimeter – 1 (desired RH 75 –80 percent)				
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.0	0.60	3	40	4.863	73.35	22.97	84.50
2	19.9	0.65	6	40	4.863	75.06	23.92	85.67
3	19.8	0.69	12	40	4.863	72.58	22.54	86.70
Average	19.9	0.65	7	40	4.860	73.66	23.15	85.62
4	19.8	0.76	5	40	4.863	70.55	21.42	85.46
5	19.7	0.72	12	40	4.863	70.14	21.19	84.88
6	19.8	0.68	12	40	4.863	68.89	20.49	83.93
Average	19.8	0.70	10	40	4.860	69.86	21.00	84.76

Mice weight = 410.1 (g) Thermocouple of calorimeter-1 has problem.

Cage: 9,10,11,12				Calorimeter – 2 (desired RH 30-35 percent)				
	Concentration			Airflow	Actual temperature			
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.2	0.51	3	36	4.424	76.64	24.80	59.00
2	20.1	0.55	5	36	4.491	76.16	24.53	61.60
3	20.0	0.58	11	36	4.491	75.79	24.33	63.00
Average	20.1	0.55	6	36	4.470	76.20	24.55	61.20
4	19.9	0.66	4	40	5.025	77.01	25.01	66.00
5	19.9	0.65	11	40	5.025	76.40	24.67	68.15
6	19.9	0.66	14	40	5.025	76.11	24.51	68.90
Average	19.9	0.66	10	40	5.030	76.51	24.73	67.68

Mice weight=422.7 (g)

Cage: 1,2,3,4				Calorimeter – 3 (desired RH 30-35percent)				
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.2	0.50	3	43.0	4.76	75.50	24.17	56.00
2	20.1	0.52	5	43.0	4.76	74.90	23.83	58.95
3	20.1	0.56	10	43.5	4.86	74.86	23.81	61.02
Average	20.1	0.53	6	43.2	4.79	75.09	23.94	58.66
4	20.0	0.62	5	44.5	5.04	73.44	23.02	63.78
5	20.0	0.64	11	44.5	5.04	72.53	22.52	66.54
6	20.0	0.66	13	44.5	5.04	72.37	22.43	67.87
Average	20.0	0.64	10	44.5	5.04	72.78	22.66	66.06

Mice weight = 408 (g)

Room (desired RH 35-40percent)								
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.4	0.07	3	-	-	70.20	21.22	36.00
2	20.5	0.10	6	-	-	70.77	21.54	36.90
3	20.5	0.11	12	-	-	70.70	21.50	37.20
Average	20.5	0.09	7			70.56	21.42	36.70
4	20.4	0.07	5	-	-	70.20	21.22	38.60
5	20.5	0.09	14	-	-	70.22	21.23	39.16
6	20.4	0.09	18	-	-	68.29	20.16	41.99
Average	20.5	0.09	9			70.13	21.19	38.08

Date: OCT 20,1997 **Day:** 3
Barometric pressure: 30.12 (in) **Desired temperature:** 24+-1.5 °C
Desired airflow: 5 (l/min)

Cage: 9,10,11,12				Calorimeter – 1 (desired RH 30-35 percent)				
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.1	0.55	5	41.0	4.99	61.68	16.49	50.70
2	20.1	0.62	8	41.0	4.99	53.10	11.72	53.37
3	20.0	0.65	10	41.0	4.99	53.87	12.15	55.21
Average	20.1	0.61	8	41.0	4.99	56.22	13.45	53.09
4	19.9	0.79	10	40.5	4.93	61.30	16.28	58.77
5	19.9	0.83	14	40.5	4.93	60.60	15.89	63.61
6	19.9	0.86	16	40.5	4.93	60.02	15.57	66.13
Average	19.9	0.83	13	40.5	4.93	60.64	15.91	62.84

Mice weight = 428.3 (g) Thermocouple of calorimeter-1 has problem.

Cage: 1,2,3,4				Calorimeter – 2 (desired RH 30-35 percent)				
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.2	0.42	9	40	5.03	73.76	23.20	53.13
2	20.2	0.47	9	40	5.03	73.67	23.15	56.73
3	20.1	0.49	12	40	5.03	73.72	23.18	58.04
Average	20.2	0.46	10	40	5.03	73.72	23.18	55.97
4	20.0	0.63	11	40	5.03	75.90	24.39	67.36
5	20.0	0.67	16	40	5.03	75.40	24.11	71.48
6	20.0	0.69	18	40	5.03	75.31	24.06	72.37
Average	20.0	0.66	15	40	5.03	75.54	24.19	70.40

Mice weight=413.9 (g)

Cage: 5,6,7,8				Calorimeter – 3 (desired RH 75-80 percent)				
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.1	0.50	6	45.5	5.23	-	-	75.06
2	20.1	0.50	9	45.5	5.23	74.00	23.33	75.58
3	20.1	0.54	11	45.5	5.23	74.80	23.78	77.66
Average	20.1	0.51	9	45.5	5.23	74.40	23.56	76.10
4	20.0	0.69	16	45.0	5.13	74.68	23.71	82.55
5	20.0	0.71	28	45.0	5.13	72.40	22.44	80.82
6	19.9	0.73	34	45.0	5.13	72.80	22.67	87.90
Average	20	0.71	26	45.0	5.13	73.29	22.94	83.76

Mice weight=417.5 (g)

Room (desired RH 35-40percent)								
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.6	0.07	5	-	-	65.60	18.67	46.58
2	20.7	0.06	11	-	-	65.80	18.78	46.29
3	20.7	0.07	13	-	-	67.47	19.71	47.60
Average	20.67	0.07	10			66.29	19.05	46.82
4	20.5	0.07	7	-	-	72.83	22.68	43.55
5	20.5	0.10	17	-	-	66.56	19.20	50.24
6	20.5	0.10	19	-	-	68.52	20.29	45.00
Average	20.50	0.09	14			69.30	20.72	46.26

Date: OCT 21,1997 **Day:** 4
Barometric pressure: 30.18 (in) **Desired temperature:** 24+-1.5 °C
Desired airflow: 5 (l/min)

Cage: 1,2,3,4					Calorimeter – 1 (desired RH 30-35 percent)			
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.1	0.58	13	41	4.99	75.74	24.30	53.50
2	20.0	0.58	17	41	4.99	77.54	25.30	52.27
3	20.0	0.59	22	41	4.99	77.18	25.10	56.60
Average	20.0	0.58	17	41	4.99	76.82	24.90	54.12
4	19.9	0.78	15	41	4.99	77.18	25.10	61.98
5	19.9	0.81	27	41	4.99	75.92	24.40	62.71
6	20.0	0.85	28	41	4.99	76.64	24.80	64.03
Average	20.0	0.81	23	41	4.99	76.58	24.77	62.91

Mice weight=420.3 (g)

Cage: 5,6,7,8					Calorimeter – 2 (desired RH 75-80 percent)			
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.1	0.55	29	39.5	4.96	73.73	23.18	74.05
2	20.0	0.55	40	39.0	4.89	75.03	23.91	72.41
3	20.1	0.55	47	39.0	4.89	74.97	23.87	74.70
Average	20.1	0.55	39	39.2	4.91	74.58	23.65	73.72
4	20.1	0.67.	59	39.0	4.89	75.47	24.15	79.25
5	20.1	0.67	75	39.0	4.89	76.45	24.69	78.26
6	20.1	0.66	78	39.5	4.96	77.56	25.31	77.23
Average	20.1	0.67	71	39.2	4.91	76.49	24.72	78.25

Mice weight=424.7 (g)

Cage: 9,10,11,12					Calorimeter – 3 (desired RH 30 –35 percent)			
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.1	0.56	8	44	4.95	73.40	23.00	61.25
2	20.1	0.58	15	44	4.95	74.93	23.85	61.65
3	20.1	0.57	21	44	4.95	72.64	22.58	64.94
Average	20.1	0.57	15	44	4.95	73.66	23.14	62.61
4	20.3	0.63	16	44.0	4.95	73.74	23.19	64.76
5	20.1	0.65	28	43.5	4.86	75.19	23.99	65.74
6	20.1	0.73	28	44.0	4.95	76.70	24.83	68.04
Average	20.2	0.67	24	44.0	4.92	75.21	24.01	66.18

Mice weight=437.1 (g)

Room (desired RH 35-40percent)								
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.6	0.06	9	-	-	71.14	21.744	42.67
2	20.6	0.06	16	-	-	70.86	21.589	40.33
3	20.5	0.06	22	-	-	70.77	21.539	43.16
Average	20.6	0.06	16			70.92	21.62	42.05
4	20.6	0.07	14	-	-	72.63	22.572	37.20
5	20.5	0.10	29	-	-	74.23	23.461	34.86
6	20.5	0.10	34	-	-	74.25	23.472	33.30
Average	20.5	0.09	26			73.70	23.17	35.12

Date: OCT 22,1997 **Day:** 5
Barometric pressure: 30.19 (in) **Desired temperature:** 24+-1.5 °C
Desired airflow: 5 (l/min)

Cage: 5,6,7,8					Calorimeter – 1 (desired RH 75-80 percent)			
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.1	0.59	40	41	4.99	75.84	24.36	76.84
2	20.1	0.58	44	41	4.99	77.36	25.20	78.21
3	20.0	0.60	48	41	4.99	77.54	25.30	77.36
Average	20.1	0.59	44	41	4.99	76.91	24.95	77.47
4	19.8	0.82	68	41	4.99	77.90	25.50	77.63
5	19.9	0.81	73	41	4.99	77.54	25.30	78.32
6	19.9	0.82	88	41	4.99	77.19	25.11	77.11
Average	20.0	0.82	76	41	4.99	77.54	25.30	77.69

Mice weight=427.8 (g)

Cage: 9,10,11,12					Calorimeter – 2 (desired RH 30-35 percent)			
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.2	0.43	22	39.5	4.96	76.59	24.77	49.85
2	20.2	0.45	27	40.0	5.03	78.90	26.06	48.26
3	20.2	0.47	31	40.0	5.03	75.96	24.42	54.20
Average	20.2	0.45	27	39.8	5.00	77.15	25.08	50.77
4	20	0.61	23	39.5	4.96	76.57	24.76	56.64
5	20	0.58	25	39.5	4.96	76.37	24.65	56.78
6	20	0.58	28	39.5	4.96	77.19	25.11	57.11
Average	20	0.59	25	39.5	4.96	76.71	24.84	56.84

Mice weight=445.5 (g)

Cage: 1,2,3,4					Calorimeter – 3 (desired RH 30-35 percent)			
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.2	0.49	14	44.0	4.95	76.42	24.68	49.74
2	20.2	0.49	18	44.0	4.95	77.90	25.50	52.62
3	20.3	0.47	22	43.5	4.86	75.78	24.32	52.73
Average	20.2	0.48	18	43.8	4.92	76.70	24.83	51.70
4	20.2	0.73	-4	44.0	4.95	75.63	24.24	60.90
5	20.1	0.68	0	43.5	4.86	75.96	24.42	61.49
6	20.1	0.68	4	43.5	4.86	76.82	24.90	61.77
Average	20.1	0.70	0	43.7	4.89	76.14	24.52	61.39

Mice weight=429.5 (g) PhD meter has problem

Room (desired RH 35-40percent)								
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.4	0.05	10	-	-	74.45	23.58	28.32
2	20.4	0.06	18	-	-	68.10	20.06	33.01
3	20.5	0.06	20	-	-	72.75	22.64	33.78
Average	20.4	0.06	16			71.77	22.09	31.70
4	20.3	0.06	6	-	-	68.76	20.42	37.21
5	20.3	0.06	8	-	-	73.67	23.15	35.12
6	20.3	0.06	10	-	-	74.83	23.79	33.41
Average	20.3	0.06	8			72.42	22.46	35.25

Date: OCT 23,1997 **Day:** 6
Barometric pressure: 29.89 (in) **Desired temperature:** 24+-1.5 °C
Desired airflow: 5 (l/min) **PhD meter has problem in the morning.**

Cage: 9,10,11,12					Calorimeter – 1 (desired RH 30-35 percent)			
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20	0.62	-	41.0	4.99	74.84	23.80	52.30
2	20	0.62	-	41.5	5.06	75.02	23.90	52.40
3	20	0.62	-	41.0	4.99	75.02	23.90	52.95
Average	20	0.62		41.2	5.02	74.96	23.87	52.55
4	20	0.76	31	41	4.99	75.92	24.40	55.21
5	20	0.75	31	41	4.99	76.28	24.60	56.36
6	20	0.75	33	41	4.99	77.18	25.10	55.05
Average	20	0.75	32	41	4.99	76.46	24.70	55.54

Mice weight=454.1 (g)

Cage: 1,2,3,4				Calorimeter – 2 (desired RH 30-35 percent)				
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.1	0.48	-	36	4.49	75.74	24.30	53.20
2	20.1	0.48	-	36	4.49	75.20	24.00	53.70
3	20.1	0.47	-	36	4.49	75.38	24.10	53.90
Average	20.1	0.48		36	4.49	75.44	24.13	53.60
4	20	0.64	26	39	4.89	78.95	26.08	50.74
5	20	0.64	26	39	4.89	77.00	25.00	56.41
6	20	0.64	27	39	4.89	77.77	25.43	56.17
Average	20	0.64	26	39	4.89	77.91	25.50	54.44

Mice weight=437.1 (g)

Cage: 5,6,7,8				Calorimeter – 3 (desired RH 75 –80 percent)				
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	19.8	0.73	-	44	4.9486	76.46	24.70	74.60
2	19.8	0.72	-	44	4.9486	73.58	23.10	75.50
3	19.8	0.70	-	44	4.9486	75.74	24.30	73.90
Average	19.8	0.72		44	4.950	75.26	24.03	74.67
4	19.9	0.81	73	45	5.1334	78.70	25.94	76.39
5	20.0	0.84	81	45	5.1334	76.03	24.46	81.56
6	20.0	0.82	83	45	5.1334	76.97	24.98	80.82
Average	20.0	0.82	79	45	5.130	77.23	25.13	79.59

Mice weight=433.2 (g)

Room (desired RH 35-40percent)								
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.6	0.05	-	-	-	65.40	18.56	40.57
2	20.6	0.05	-	-	-	66.20	19.00	40.80
3	20.6	0.05	-	-	-	64.80	18.22	41.20
Average	20.6	0.05				65.47	18.59	40.86
4	20.6	0.07	0	-	-	71.86	22.14	32.52
5	20.0	0.07	0	-	-	74.11	23.39	32.71
6	20.0	0.07	0	-	-	75.16	23.98	31.30
Average	20.2	0.07	0			73.71	23.17	32.18

Date: OCT 24,1997 **Day:** 7
Barometric pressure: 29.79 (in) **Desired temperature:** 24+-1.5 °C
Desired airflow: 5 (l/min)

Cage: 1,2,3,4					Calorimeter – 1 (desired RH 30-35 percent)			
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.2	0.46	30	41	4.99	81.68	27.60	39.82
2	20.2	0.46	37	41	4.99	81.68	27.60	40.92
3	20.1	0.49	40	41	4.99	82.04	27.80	43.86
Average	20.2	0.47	36	41	4.99	81.80	27.67	41.53
4	19.9	0.79	30	41	4.99	78.98	26.10	51.32
5	19.9	0.83	41	41	4.99	79.52	26.40	53.06
6	20.0	0.84	43	41	4.99	79.52	26.40	53.52
Average	19.9	0.82	38	41	4.99	79.34	26.30	52.63

Mice weight=441.1 (g)

Cage: 5,6,7,8					Calorimeter – 2 (desired RH 75-80 percent)			
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.0	0.49	67	39	4.89	76.60	24.78	74.94
2	20.1	0.51	71	39	4.89	76.50	24.72	75.92
3	20.0	0.53	70	39	4.89	76.60	24.78	76.62
Average	20.0	0.51	69	39	4.89	76.57	24.76	75.83
4	20.0	0.70	99	39	4.89	76.27	24.59	76.27
5	20.0	0.68	105	39	4.89	76.14	24.52	76.14
6	20.2	0.64	107	39	4.89	76.38	24.66	76.38
Average	20.1	0.67	104	39	4.89	76.26	24.59	76.26

Mice weight=442.8 (g)

Cage: 9,10,11,12					Calorimeter – 3 (desired RH 30-35 percent)			
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.1	0.54	51	44	4.9486	76.40	24.67	54.23
2	20.1	0.55	64	44	4.9486	76.40	24.67	55.50
3	20.1	0.55	67	44	4.9486	76.40	24.67	56.65
Average	20.1	0.55	61	44	4.9500	76.40	24.67	55.46
4	20.0	0.81	52	43	4.7638	74.76	23.76	61.31
5	20.0	0.86	52	43	4.7638	75.31	24.06	62.92
6	20.0	0.78	55	46	5.3182	75.31	24.06	62.86
Average	20.00	0.82	53	44	4.9500	75.13	23.96	62.36

Mice weight=461.2 (g)

Room (desired RH 35-40 percent)								
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.7	0.05	11	-	-	71.7	22.06	31.49
2	20.7	0.05	10	-	-	71.4	21.89	31.93
3	20.7	0.05	12	-	-	71.5	21.94	32.81
Average	20.7	0.05	11			71.53	21.96	32.08
4	20.8	0.07	0	-	-	70.60	21.44	44.43
5	20.5	0.07	0	-	-	70.52	21.40	43.75
6	20.8	0.07	3	-	-	69.43	20.79	43.79
Average	20.7	0.07	1			70.18	21.21	43.99

Date: OCT 25,1997 **Day:** 8
Barometric pressure: 29. 68 (in) **Desired temperature:** 24+-1.5 °C
Desired airflow: 5 (l/min)

Cage: 5,6,7,8				Calorimeter – 1 (desired RH 75-80 percent)				
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.2	0.63	90	40	4.86	76.58	24.77	89.44
2	20.0	0.64	86	40	4.86	76.50	24.72	89.71
3	20.1	0.68	83	40	4.86	77.34	25.19	90.28
Average	20.1	0.65	86	40	4.86	76.81	24.89	89.81
4	20.2	0.77	132	43	5.26	-	-	80.41
5	20.1	0.79	140	41	4.99	-	-	81.41
6	20.2	0.79	146	43	5.26	-	-	81.46
Average	20.2	0.78	139	42	5.17			81.09

Mice weight=449.4 (g)

Cage: 9,10,11,12				Calorimeter – 2 (desired RH 30-35 percent)				
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.3	0.44	38	39.0	4.89	76.36	24.64	49.62
2	20.3	0.46	36	39.0	4.89	76.19	24.55	50.83
3	20.4	0.47	37	39.5	4.96	76.30	24.61	50.79
Average	20.3	0.46	37	39.2	4.91	76.28	24.60	50.41
4	20.3	0.58	34	40	5.03	76.45	24.69	51.53
5	20.3	0.61	44	41	5.16	76.50	24.72	55.23
6	20.3	0.63	45	40	5.03	76.25	24.58	55.58
Average	20.3	0.61	41	40	5.07	76.40	24.67	54.11

Mice weight=464.1 (g)

Cage: 1,2,3,4					Calorimeter – 3 (desired RH 30-35 percent)			
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.4	0.44	30	41	4.39	75.79	24.33	46.52
2	20.3	0.44	33	41	4.39	75.44	24.13	49.97
3	20.3	0.47	31	41	4.39	75.67	24.26	49.98
Average	20.3	0.45	31	41	4.39	75.63	24.24	48.82
4	20.3	0.75	34	44	4.95	74.87	23.82	53.89
5	20.1	0.86	36	44	4.95	74.83	23.79	59.57
6	20.1	0.93	41	44	4.95	76.01	24.45	61.83
Average	20.2	0.85	37	44	4.95	75.24	24.02	58.43

Mice weight=449.9 (g)

Room (desired RH 35-40 percent)								
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.6	0.09	3	-	-	69.75	20.97	41.50
2	20.6	0.09	3	-	-	71.16	21.76	41.21
3	20.6	0.09	5	-	-	70.78	21.54	41.74
Average	20.6	0.09	4			70.56	21.42	41.48
4	21.0	0.05	0	-	-	70.84	21.58	42.13
5	21.0	0.05	1	-	-	70.08	21.16	41.70
6	20.9	0.06	0	-	-	71.99	22.22	40.82
Average	21.0	0.05	0			70.97	21.65	41.55

Date: OCT 26,1997 **Day:** 9
Barometric pressure: 29.52 (in) **Desired temperature:** 24+-1.5 °C
Desired airflow: 5 (l/min)

Cage: 9,10,11,12					Calorimeter – 1 (desired RH 30-35 percent)			
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.1	0.55	56	41	4.99	-	-	52.10
2	20.1	0.57	56	43	5.26	-	-	52.47
3	20.0	0.60	52	43	5.26	-	-	53.94
Average	20.1	0.57	55	42	5.17			52.84
4	20.1	0.74	99	41	4.99	77.15	25.08	59.67
5	20.1	0.74	97	41	4.99	76.90	24.94	59.30
6	20.1	0.75	97	41	4.99	77.05	25.03	61.56
Average	20.1	0.74	98	41	4.99	77.03	25.02	60.18

Mice weight=471.9 (g)

Cage: 1,2,3,4				Calorimeter – 2 (desired RH 30-35 percent)				
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.3	0.46	56	40	5.15	76.28	24.60	57.20
2	20.2	0.47	54	40	5.15	76.40	24.67	56.59
3	20.2	0.47	49	40	5.15	76.37	24.65	55.98
Average	20.2	0.47	53	40	5.15	76.35	24.64	56.59
4	20.2	0.54	88	39.5	5.08	76.03	24.46	60.24
5	20.2	0.56	82	40.0	5.15	76.16	24.53	60.33
6	20.2	0.57	80	39.5	5.08	75.97	24.43	63.66
Average	20.2	0.56	83	39.7	5.10	76.05	24.47	61.41

Mice weight=449.7 (g)

Cage: 5,6,7,8				Calorimeter – 3 (desired RH 75-80 percent)				
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	19.9	0.70	72	44	4.95	74.60	23.67	82.60
2	19.8	0.73	74	44	4.95	74.44	23.58	80.41
3	19.9	0.74	72	44	4.95	74.40	23.56	79.72
Average	19.9	0.72	73	44	4.95	74.48	23.60	80.91
4	20.1	0.82	134	44	4.95	75.23	24.02	82.66
5	20.1	0.79	135	44	4.95	75.08	23.93	84.04
6	20.0	0.77	130	44	4.95	74.71	23.73	83.64
Average	20.1	0.79	133	44	4.95	75.01	23.89	83.45

Mice weight=454.7 (g)

Room (desired RH 35-40 percent)								
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.6	0.1	3	-	-	71.24	21.80	41.20
2	20.5	0.1	7	-	-	70.50	21.39	40.23
3	20.6	0.1	7	-	-	70.64	21.47	39.89
Average	20.6	0.1	6			70.79	21.55	40.44
4	20.7	0.10	14	-	-	70.35	21.31	41.21
5	20.7	0.10	15	-	-	70.31	21.28	41.69
6	20.7	0.11	13	-	-	70.75	21.53	41.50
Average	20.7	0.10	14			70.47	21.37	41.47

Date: OCT 27,1997 **Day:** 10
Barometric pressure: 29.98 (in) **Desired temperature:** 24+-1.5 °C
Desired airflow: 5 (l/min)

Cage: 1,2,3,4					Calorimeter – 1 (desired RH 30-35 percent)			
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp (°C)	Actual RH (percent)
1	20.2	0.48	96	41.0	4.99	76.69	24.83	50.40
2	20.1	0.52	94	41.5	5.06	77.09	25.05	53.11
3	20.1	0.54	100	41.5	5.06	76.38	24.66	54.63
Average	20.1	0.51	97	41.3	5.04	76.72	24.84	52.71
4	20.1	0.63	125	41.5	5.06	77.04	25.02	56.05
5	20.1	0.64	108	41.5	5.06	77.89	25.49	56.73
6	20.1	0.67	103	41.5	5.06	76.95	24.97	58.57
Average	20.1	0.65	112	41.5	5.06	77.29	25.16	57.12

Mice weight=459.4 (g)

Cage: 5,6,7,8					Calorimeter – 2 (desired RH 75-80 percent)			
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp (°C)	Actual RH (percent)
1	20.2	0.48	70	40	5.03	76.09	24.49	78.40
2	20.1	0.51	68	40	5.03	76.08	24.49	80.46
3	20.1	0.55	71	40	5.03	76.14	24.52	82.01
Average	20.1	0.51	70	40	5.03	76.10	24.50	80.29
4	20.1	0.60	105	40	5.03	76.09	24.49	79.66
5	20.1	0.60	103	40	5.03	76.14	24.52	80.60
6	20.1	0.56	95	40	5.03	76.14	24.52	81.68
Average	20.1	0.59	101	40	5.03	76.12	24.51	80.65

Mice weight=461.1 (g)

Cage: 9,10,11,12					Calorimeter – 3 (desired RH 30-35 percent)			
	Concentration		Airflow			Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp (°C)	Actual RH (percent)
1	20.2	0.52	50	44	4.95	75.36	24.09	51.36
2	20.2	0.54	45	44	4.95	75.39	24.11	53.65
3	20.1	0.57	54	44	4.95	75.31	24.06	55.67
Average	20.2	0.54	50	44	4.95	75.35	24.09	53.56
4	20.2	0.72	85	44	4.95	75.27	24.04	59.30
5	20.1	0.71	68	44	4.95	75.30	24.06	59.64
6	20.1	0.71	65	44	4.95	75.21	24.01	62.41
Average	20.1	0.713	73	44	4.95	75.26	24.03	60.45

Mice weight=478.3 (g)

Room (desired RH 35-40 percent)								
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.6	0.08	10	-	-	71.41	21.89	39.50
2	20.6	0.07	12	-	-	71.66	22.03	40.67
3	20.6	0.07	14	-	-	70.36	21.31	40.03
Average	20.6	0.07	12			71.14	21.75	40.07
4	20.7	0.06	10	-	-	69.96	21.09	39.25
5	20.7	0.06	8	-	-	70.69	21.49	39.80
6	20.7	0.06	10	-	-	71.06	21.70	37.69
Average	20.7	0.06	9			70.57	21.43	38.91

3.4.1.2 Raw Data for Test 2

Date: DEC 13,1997 **Day:** 1

Barometric pressure: 29.77 (in) **Desired temperature:** 24+-1.5 °C

Desired airflow: 5 (l/min)

Cage: 1,2,3,4					Calorimeter – 1 (desired RH 30-35 percent)			
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.1	0.61	0	42.8	5.01	72.15	22.31	65.21
2	20.1	0.64	-1	42.0	4.89	72.05	22.25	68.00
3	20.3	0.63	0	43.0	5.04	71.83	22.13	68.50
Average	20.2	0.63	0	42.6	4.98	72.01	22.23	67.24
4	20.0	0.75	1	43.0	5.04	72.24	22.36	69.48
5	20.0	0.75	2	42.0	4.89	72.03	22.24	70.06
6	20.0	0.72	2	43.0	5.04	71.95	22.19	69.67
Average	20.0	0.74	2	42.7	4.99	72.07	22.26	69.74

Mice weight=411.7 (g) Morning: NH_3(tube)=0 ppm Afternoon: NH_3 (tube)=0ppm

Cage: 5,6,7,8					Calorimeter – 2 (desired RH 75-80 percent)			
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.0	0.60	1	42.2	4.99	73.28	22.93	73.80
2	20.0	0.68	1	42.9	5.10	73.80	23.22	77.10
3	20.2	0.64	0	42.5	5.04	73.49	23.05	75.60
Average	20.1	0.64	1	42.5	5.04	73.52	23.07	75.50
4	19.9	0.70	2	42.0	4.96	73.42	23.01	74.15
5	19.9	0.70	2	42.5	5.04	73.38	22.99	74.52
6	20.0	0.70	3	42.2	4.99	73.30	22.94	73.14
Average	19.9	0.70	2	42.2	4.99	73.37	22.98	73.94

Mice weight=415.9 (g) Morning: NH_3 (tube)=1 ppm Afternoon: NH_3 (tube)=0ppm

Cage: 9,10,11,12					Calorimeter – 3 (desired RH 75-80 percent)			
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.0	0.67	0	42.5	4.95	72.13	22.29	70.00
2	20.0	0.67	0	43.0	5.03	74.21	23.45	73.20
3	20.2	0.68	0	42.7	4.98	73.34	22.97	75.90
Average	20.1	0.67	0	42.7	4.99	73.23	22.90	73.03
4	20.0	0.73	2	42.8	5.00	72.91	22.73	74.38
5	19.9	0.77	2	42.0	4.87	73.20	22.89	73.86
6	19.9	0.76	3	42.0	4.87	74.12	23.40	74.53
Average	19.9	0.75	2	42.3	4.91	73.41	23.01	74.26

Mice weight=415.9 (g) Morning: NH_3 (tube)=0 ppm Afternoon: NH_3 (tube)=0ppm.

Room (desired RH 35-40 percent)								
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.8	0.04	-1	-	-	66.39	19.11	37.90
2	20.7	0.03	-1	-	-	65.00	18.33	38.30
3	20.7	0.03	0	-	-	64.74	18.19	38.10
Average	20.7	0.03	-1			65.38	18.54	38.10
4	20.8	0.04	3	-	-	65.91	18.84	39.53
5	20.8	0.05	3	-	-	65.63	18.68	39.62
6	20.8	0.05	3	-	-	64.79	18.22	39.25
Average	20.8	0.05	3			65.44	18.58	39.47

Morning: NH_3 (tube)=0 ppm Afternoon: NH_3 (tube)= 0 ppm

Date: DEC 14,1997 **Day:** 2
Barometric pressure: 29.77 (in) **Desired temperature:** 24+-1.5 °C
Desired airflow: 5 (l/min)

Cage: 1,2,3,4				Calorimeter – 3 (desired RH 30-35 percent)				
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.0	0.64	3	42.8	5.00	73.87	23.26	54.00
2	20.0	0.60	3	42.7	4.98	73.30	22.94	62.00
3	19.9	0.62	3	42.7	4.98	74.70	23.72	65.80
Average	20.0	0.62	3	42.7	4.99	73.96	23.31	60.60
4	20.2	0.80	0	42.6	4.96	74.74	23.74	57.00
5	19.8	0.75	0	42.5	4.95	74.62	23.68	61.00
6	19.8	0.72	0	42.8	5.00	73.88	23.27	60.70
Average	19.9	0.76	0	42.6	4.97	74.41	23.56	59.57

Mice weight=417.1 (g) Morning: NH_3 (tube)=0 ppm Afternoon: NH_3 (tube)=0ppm

Cage: 5,6,7,8				Calorimeter – 1 (desired RH 75-80 percent)				
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.0	0.65	3	42.7	5.00	72.24	22.36	82.80
2	20.0	0.66	3	42.5	4.97	72.58	22.54	81.60
3	20.0	0.63	3	42.8	5.01	72.61	22.56	80.90
Average	20.0	0.65	3	42.7	4.99	72.48	22.49	81.77
4	19.7	0.78	0	43.5	5.12	73.24	22.91	82.60
5	19.6	0.84	1	42.7	5.00	73.24	22.91	84.20
6	19.7	0.75	1	42.7	5.00	72.85	22.69	83.70
Average	19.7	0.79	1	43.0	5.04	73.11	22.84	83.50

Mice weight=415.2 (g) Morning: NH_3 (tube)=0 ppm Afternoon: NH_3 (tube)=0ppm

Cage: 9,10,11,12						Calorimeter – 2 (desired RH 75-80 percent)		
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.0	0.6	3	42.5	5.04	73.64	23.13	83.30
2	20.4	0.61	4	42.2	4.99	73.45	23.03	83.10
3	20.2	0.68	4	42.5	5.04	73.59	23.11	82.60
Average	20.2	0.63	4	42.4	5.02	73.56	23.09	83.00
4	19.6	0.75	0	40.0	4.65	74.40	23.56	74.30
5	19.9	0.68	1	42.2	4.99	74.41	23.56	83.70
6	19.7	0.76	1	42.3	5.00	74.06	23.37	83.30
Average	19.7	0.73	1	41.5	4.88	74.29	23.49	80.43

Mice weight=420.6 (g) Morning: NH_3 (tube)=0 ppm Afternoon: NH_3 (tube)=0ppm

Room (desired RH 35-40 percent)								
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.8	0.06	2	-	-	66.50	19.17	37.50
2	20.7	0.05	3	-	-	66.78	19.32	37.00
3	20.7	0.07	3	-	-	66.86	19.37	37.40
Average	20.7	0.06	3			66.71	19.29	37.30
4	20.6	0.05	1	-	-	67.57	19.76	37.80
5	20.6	0.05	1	-	-	67.49	19.72	38.30
6	20.6	0.05	1	-	-	67.16	19.53	38.00
Average	20.60	0.05	1			67.41	19.67	38.03

Morning: NH_3 (tube)=0 ppm Afternoon: NH_3=0 ppm

Date: DEC 15,1997 **Day:** 3
Barometric pressure: 29.84 (in) **Desired temperature:** 24+-1.5 °C
Desired airflow: 5 (l/min)

Cage: 1,2,3,4						Calorimeter – 2 (desired RH 30-35 percent)		
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.1	0.55	1	43	5.11	76.81	24.89	53.68
2	20.1	0.54	2	42	4.96	76.80	24.89	54.14
3	20.1	0.55	2	42	4.96	76.32	24.62	55.57
Average	20.1	0.55	2	42	5.01	76.64	24.80	54.46
4	19.9	0.80	0	42	4.96	77.28	25.16	61.06
5	19.9	0.77	1	42	4.96	77.09	25.05	63.04
6	20.0	0.75	2	42	4.96	76.38	24.66	63.83
Average	19.9	0.77	1	42	4.96	76.92	24.95	62.64

Mice weight=426.9 (g) Morning: NH_3 (tube)=0 ppm Afternoon: NH_3 (tube)=0ppm

Cage: 5,6,7,8					Calorimeter – 3 (desired RH 75-80 percent)			
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.0	0.60	1	44.0	5.19	75.12	23.96	75.35
2	20.0	0.61	2	44.0	5.19	73.97	23.32	73.66
3	19.9	0.63	3	43.5	5.11	72.74	22.63	75.16
Average	20.0	0.61	2	43.8	5.16	73.94	23.30	74.72
4	20.0	0.77	1	43.0	5.03	75.02	23.90	77.91
5	19.9	0.77	2	43.0	5.03	75.12	23.96	80.42
6	20.0	0.75	2	43.5	5.11	75.22	24.01	80.13
Average	20.0	0.76	2	43.2	5.05	75.12	23.96	79.49

Mice weight=418.1 (g) Morning: NH_3 (tube)=0 ppm Afternoon: NH_3 (tube)=0ppm

Cage: 9,10,11,12					Calorimeter – 1 (desired RH 75-80 percent)			
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.1	0.62	1	43.0	5.04	76.96	24.98	82.96
2	20.1	0.62	2	42.5	4.97	76.19	24.55	83.45
3	20.0	0.61	2	42.0	4.89	76.33	24.63	82.19
Average	20.1	0.62	2	42.5	4.97	76.49	24.72	82.87
4	19.8	0.91	0	42.0	4.89	78.08	25.60	83.06
5	19.9	0.87	2	42.0	4.89	77.59	25.33	84.22
6	19.8	0.86	2	42.0	4.89	77.56	25.31	85.83
Average	19.8	0.88	1	42.0	4.89	77.74	25.41	84.37

Mice weight=424.9 (g) Morning: NH_3 (tube)=0 ppm Afternoon: NH_3 (tube)=0ppm

Room (desired RH 35-40 percent)								
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.6	0.05	1	-	-	69.33	20.74	35.84
2	20.6	0.04	2	-	-	70.14	21.19	34.79
3	20.6	0.04	2	-	-	70.42	21.34	36.89
Average	20.6	0.04	2			69.96	21.09	35.84
4	20.7	0.06	1	-	-	70.90	21.61	35.25
5	20.7	0.06	2	-	-	70.08	21.16	35.80
6	20.7	0.06	2	-	-	70.97	21.65	36.07
Average	20.7	0.06	2			70.65	21.47	35.71

Morning: NH_3 (tube)=0 ppm Afternoon: NH_3 (tube)=0 ppm

Date: DEC 16,1997 **Day:** 4
Barometric pressure: 29.94 (in) **Desired temperature:** 24+-1.5 °C
Desired airflow: 5 (l/min)

Cage: 1,2,3,4				Calorimeter – 1 (desired RH 30-35 percent)				
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.1	0.54	2	42.0	4.89	76.69	24.83	57.36
2	20.1	0.55	2	42.5	4.97	76.83	24.91	56.05
3	20.1	0.57	2	42.0	4.89	76.84	24.91	57.89
Average	20.1	0.55	2	42.2	4.92	76.79	24.88	57.10
4	19.9	0.81	5	42.0	4.89	77.57	25.32	62.12
5	19.9	0.79	6	42.0	4.89	77.24	25.13	63.67
6	19.9	0.79	6	42.0	4.89	76.95	24.97	65.31
Average	19.9	0.80	6	42.0	4.89	77.25	25.14	63.70

Mice weight=437.4 (g) Morning: NH_3 (tube)=1 ppm Afternoon: NH_3 (tube)=1ppm

Cage: 5,6,7,8				Calorimeter – 2 (desired RH 75-80 percent)				
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.0	0.58	2	42.5	5.04	76.30	24.61	77.94
2	19.9	0.60	2	42.0	4.96	76.19	24.55	78.99
3	20.0	0.60	2	42.0	4.96	76.19	24.55	79.60
Average	20.0	0.59	2	42.2	4.98	76.23	24.57	78.84
4	19.9	0.72	6	42.0	4.96	76.38	24.66	83.70
5	19.9	0.72	7	42.0	4.96	75.96	24.42	83.32
6	20.0	0.74	8	42.0	4.96	75.89	24.38	84.44
Average	19.9	0.73	7	42.0	4.96	76.08	24.49	83.82

Mice weight=427.1 (g) Morning: NH_3 (tube) = 1.5 ppm Afternoon: NH_3 (tube) = 8ppm

Cage: 9,10,11,12				Calorimeter – 3 (desired RH 75-80 percent)				
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.0	0.59	2	44.5	5.27	74.28	23.49	73.42
2	20.1	0.59	2	43.0	5.03	74.45	23.58	73.37
3	19.9	0.62	3	43.0	5.03	75.21	24.01	75.35
Average	20.0	0.60	2	43.5	5.11	74.65	23.69	74.05
4	19.8	0.82	8	43.0	5.03	74.50	23.61	78.59
5	19.7	0.83	10	43.0	5.03	74.28	23.49	78.49
6	19.7	0.85	12	43.0	5.03	75.29	24.05	81.24
Average	19.7	0.83	10	43.0	5.03	74.69	23.72	79.44

Mice weight=433 (g) Morning: NH_3 (tube)=8 ppm Afternoon: NH_3 (tube)=10 ppm

Room (desired RH 35-40 percent)								
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.7	0.06	2	-	-	69.44	20.80	36.07
2	20.7	0.06	2	-	-	69.45	20.81	36.12
3	20.7	0.06	2	-	-	69.36	20.76	35.98
Average	20.7	0.06	2			69.42	20.79	36.06
4	20.7	0.06	6	-	-	69.51	20.84	37.89
5	20.7	0.06	6	-	-	69.43	20.79	38.07
6	20.6	0.06	7	-	-	69.14	20.63	38.02
Average	20.7	0.06	6			69.36	20.76	37.99

Morning: NH_3 (tube)=0 ppm Afternoon: NH_3 (tube)=0 ppm

Date: DEC 17,1997 **Day:** 5
Barometric pressure: 30.04 (in) **Desired temperature:** 24+-1.5 °C
Desired airflow: 5 (l/min)

Cage: 1,2,3,4					Calorimeter – 3 (desired RH 30-35 percent)			
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.1		9	43.5	5.11	75.41	24.12	58.89
2	20.1		9	43.5	5.11	75.80	24.33	60.05
3	20.0		11	43.0	5.03	75.54	24.19	62.46
Average	20.1		10	43.3	5.08	75.58	24.21	60.47
4	19.7	0.68	11	44.0	5.19	75.67	24.26	62.61
5	19.7	0.62	11	43.0	5.03	74.06	23.37	64.78
6	19.7	0.57	12	43.0	5.03	74.87	23.82	65.94
Average	19.7	0.62	11	43.3	5.08	74.87	23.81	64.44

Mice weight=442 (g) Morning: NH_3 (tube)=1 ppm Afternoon: NH_3 (tube)=1.5 ppm

Cage: 5,6,7,8					Calorimeter – 1 (desired RH 75-80 percent)			
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	19.9		9	42.5	4.97	74.37	23.54	77.63
2	20.0		15	42.5	4.97	75.11	23.95	77.44
3	20.1		19	43.0	5.04	75.17	23.98	78.94
Average	20.0		14	43.0	4.99	74.88	23.82	78.00
4	19.6	0.73	39	43.0	5.04	76.38	24.66	85.53
5	19.7	0.71	41	43.0	5.04	76.52	24.73	84.90
6	19.6	0.70	42	43.0	5.04	73.83	23.24	90.14
Average	19.6	0.71	41	43.0	5.04	75.58	24.21	86.86

Mice weight=434.2 (g) Morning: NH_3 (tube)=21 ppm Afternoon: NH_3 (tube)=46 ppm

Cage: 9,10,11,12					Calorimeter – 2 (desired RH 75-80 percent)			
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.0		36	42.5	5.04	76.55	24.75	75.17
2	19.9		47	43.0	5.11	76.76	24.87	77.43
3	19.9		45	43.0	5.11	76.00	24.44	79.14
Average	19.9		43	42.8	5.09	76.44	24.69	77.25
4	19.6	0.69	69	42.0	4.96	77.88	25.49	80.61
5	19.7	0.67	67	42.0	4.96	76.65	24.81	82.37
6	19.7	0.68	60	42.0	4.96	75.52	24.18	85.46
Average	19.7	0.68	65	42.0	4.96	76.68	24.82	82.81

Mice weight=441.2 (g) Morning: NH_3 (tube)=57 ppm Afternoon: NH_3 (tube)=76 ppm

Room (desired RH 35-40 percent)								
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.7		4	-	-	70.95	21.64	35.93
2	20.8		5	-	-	68.95	20.53	36.34
3	20.8		7	-	-	72.13	22.29	38.71
Average	20.7		5			70.68	21.49	36.99
4	20.6	0.06	8	-	-	72.32	22.40	35.61
5	20.6	0.03	8	-	-	66.16	18.98	41.22
6	20.6	0.03	9	-	-	65.85	18.81	42.49
Average	20.6	0.04	8			68.11	20.06	39.77

Morning: NH_3 (tube)=0 ppm Afternoon: NH_3 (tube)=0 ppm

Date: DEC 18,1997 **Day:** 6
Barometric pressure: 29.82 (in) **Desired temperature:** 24+-1.5 °C
Desired airflow: 5 (l/min)

Cage: 1,2,3,4					Calorimeter – 2 (desired RH 30-35 percent)			
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.2	0.49	12	42.0	4.89	79.30	26.28	50.91
2	20.1	0.52	16	42.0	4.89	79.35	26.31	51.79
3	19.7	0.54	18	42.0	4.89	78.25	25.69	52.85
Average	20.0	0.52	15	42.0	4.89	78.97	26.09	51.85
4	19.8	0.86	19	42.0	4.89	76.79	24.88	56.22
5	19.8	0.65	22	42.0	4.89	76.67	24.82	59.03
6	19.8	0.47	22	42.5	4.97	76.59	24.77	58.61
Average	19.8	0.66	21	42.2	4.92	76.68	24.82	57.95

Mice weight=447.1 (g) Morning: NH_3 (tube)=4 ppm Afternoon: NH_3 (tube)=5 ppm

Cage: 5,6,7,8					Calorimeter – 3 (desired RH 75-80 percent)			
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.0	0.49	84	43.0	5.11	75.75	24.31	73.04
2	19.8	0.50	81	43.0	5.11	75.00	23.89	73.52
3	19.9	0.52	76	43.0	5.11	74.20	23.44	73.91
Average	19.9	0.50	80	43.0	5.11	74.98	23.88	73.49
4	19.9	0.88	115	44.0	5.26	75.17	23.98	76.66
5	19.8	0.56	130	43.0	5.11	75.53	24.18	74.34
6	19.9	0.56	135	43.5	5.19	76.01	24.45	76.22
Average	19.9	0.67	127	43.5	5.19	75.57	24.21	75.74

Mice weight=444.1 (g) Morning: NH_3 (tube)=85 ppm Afternoon: NH_3 (tube)=90 ppm

Cage: 9,10,11,12					Calorimeter – 1 (desired RH 75-80 percent)			
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	19.9	0.45	109	43.0	5.03	77.18	25.10	75.55
2	19.9	0.49	107	43.0	5.03	77.19	25.11	75.93
3	19.8	0.48	100	43.0	5.03	76.42	24.68	75.89
Average	19.9	0.47	105	43.0	5.03	76.93	24.96	75.79
4	19.8	0.86	113	43.0	5.03	75.45	24.14	80.54
5	19.7	0.83	132	43.0	5.03	75.45	24.14	81.41
6	19.9	0.56	130	43.0	5.03	75.42	24.12	81.36
Average	19.8	0.75	125	43.0	5.03	75.44	24.13	81.10

Mice weight=448.8 (g) Morning: NH_3 (tube)=90 ppm Afternoon: NH_3 (tube)=105 ppm

Room (desired RH 35-40 percent)								
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.7	0.06	12	-	-	66.39	19.11	37.90
2	20.5	0.06	17	-	-	65.00	18.33	38.30
3	20.3	0.07	15	-	-	64.74	18.19	38.10
Average	20.5	0.06	15			65.38	18.54	38.10
4	20.5	0.05	22	-	-	65.91	18.84	39.53
5	20.5	0.03	24	-	-	65.63	18.68	39.62
6	20.5	0.04	24	-	-	64.79	18.22	39.25
Average	20.5	0.04	23			65.44	18.58	39.47

Morning: NH_3 (tube)=0 ppm Afternoon: NH_3 (tube)=0 ppm

Date: DEC 19,1997 **Day:** 7
Barometric pressure: 29.78 (in) **Desired temperature:** 24+-1.5 °C
Desired airflow: 6 (l/min)

Cage: 1,2,3,4						Calorimeter – 1 (desired RH 30-35 percent)		
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.1	0.50	10	48.0	5.83	75.27	24.04	49.90
2	20.1	0.50		49.0	5.99	75.29	24.05	56.10
3	20.1	0.49		49.0	5.99	75.32	24.07	57.26
Average	20.1	0.50	10	48.7	5.93	75.29	24.05	54.42
4	20.1	0.72	8	48.0	5.83	73.40	23.00	63.81
5	20.0	0.73	20	48.0	5.83	74.76	23.76	63.47
6	20.0	0.72	24	48.0	5.83	73.91	23.28	64.83
Average	20.0	0.72	17	48.0	5.83	74.02	23.35	64.04

Mice weight=453 (g) Morning: NH_3 (tube)=2 ppm Afternoon: NH_3 (tube)=2 ppm

Cage: 5,6,7,8						Calorimeter – 2 (desired RH 75-80 percent)		
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.2	0.45	85	51.0	6.24	76.56	24.76	73.80
2	20.1	0.46	89	51.0	6.24	76.49	24.72	84.48
3	20.1	0.46	89	50.0	6.09	76.61	24.78	87.43
Average	20.1	0.46	88	50.7	6.19	76.55	24.75	81.90
4	19.9	0.74	122	49.0	5.94	75.96	24.42	88.26
5	19.9	0.75	135	49.0	5.94	76.38	24.66	87.53
6	19.9	0.72	147	49.0	5.94	75.64	24.24	86.79
Average	19.9	0.74	135	49.0	5.94	75.99	24.44	87.53

Mice weight=447.2 (g) Morning: NH_3 (tube)=84 ppm Afternoon: NH_3 (tube)=110 ppm

Cage: 9,10,11,12						Calorimeter – 3 (desired RH 75-80 percent)		
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.0	0.46	87	48.0	5.88	74.97	23.87	72.07
2	20.0	0.63	89	50.0	6.18	75.20	24.00	73.37
3	20.1	0.52	92	49.0	6.03	75.02	23.90	72.31
Average	20.0	0.54	89	49.0	6.03	75.06	23.92	72.58
4	19.9	0.75	139	49.0	6.03	74.99	23.88	77.14
5	19.9	0.73	153	49.0	6.03	74.95	23.86	77.23
6	19.9	0.74	149	49.0	6.03	73.80	23.22	75.20
Average	19.9	0.74	14	49.0	6.03	74.58	23.66	76.52

Mice weight=449.3 (g) Morning: NH_3 (tube)=86 ppm Afternoon: NH_3 (tube)=105 ppm

Room (desired RH 35-40 percent)								
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.8	0.06	2	-	-	66.50	19.17	37.50
2	20.7	0.05	3	-	-	66.78	19.32	37.00
3	20.7	0.07	3	-	-	66.86	19.37	37.40
Average	20.7	0.06	3			66.71	19.29	37.30
4	20.6	0.05	1	-	-	67.57	19.76	37.80
5	20.6	0.05	1	-	-	67.49	19.72	38.30
6	20.6	0.05	1	-	-	67.16	19.53	38.00
Average	20.6	0.05	1			67.41	19.67	38.03

Morning: NH_3 (tube)=0 ppm Afternoon: NH_3 (tube)=0 ppm

Date: DEC 20,1997 **Day:** 8
Barometric pressure: 29.92 (in)q **Desired temperature:** 24+-1.5 °C
Desired airflow: 5 (l/min)

Cage: 1,2,3,4				Calorimeter – 3 (desired RH 30-35 percent)				
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.3	0.29	12	60	7.71	73.20	22.89	46.10
2	20.3	0.29	22	60	7.71	73.08	22.82	46.39
3	20.3	0.31	28	60	7.71	73.12	22.84	47.41
Average	20.3	0.30	21	60	7.71	73.13	22.85	46.63
4	20.3	0.42	-	60.0	7.71	73.80	23.22	44.70
5	20.2	0.40	-	60.5	7.79	73.03	22.79	51.65
6	20.2	0.60	-	60.0	7.71	72.99	22.77	54.55
Average	20.2	0.47	-	60.2	7.74	73.27	22.93	50.30

Mice weight=459.2 (g) Morning: NH_3 (tube)=2 ppm Afternoon: NH_3 (tube)=5 ppm

Cage: 5,6,7,8				Calorimeter – 1 (desired RH 75-80 percent)				
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.2	0.33	119	61.0	7.90	72.57	22.54	78.98
2	20.2	0.37	123	60.5	7.82	72.49	22.49	77.53
3	20.1	0.36	120	61.0	7.90	72.55	22.53	75.45
Average	20.2	0.35	121	60.8	7.88	72.54	22.52	77.32
4	20.1	0.44	122	61.0	7.90	72.63	22.57	76.66
5	20.1	0.43	132	60.5	7.82	72.51	22.51	77.63
6	20.0	0.66	128	60.0	7.74	72.55	22.53	77.53
Average	20.1	0.51	127	60.5	7.82	72.56	22.54	77.27

Mice weight=453.5 (g) Morning: NH_3 (tube)=104 ppm Afternoon: NH_3 (tube)=126 ppm

Cage: 9,10,11,12						Calorimeter – 2 (desired RH 75-80 percent)		
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.1	0.29	135	60.5	7.67	74.66	23.70	80.79
2	20.1	0.37	139	60.5	7.67	74.71	23.73	78.68
3	20.1	0.33	142	60.0	7.59	74.72	23.73	76.18
Average	20.1	0.33	139	60.3	7.64	74.70	23.72	78.55
4	20.1	0.39	142	61.0	7.75	74.89	23.83	75.72
5	20.0	0.44	144	61.0	7.75	74.66	23.70	76.83
6	20.0	0.68	153	61.0	7.75	74.13	23.41	77.89
Average	20.0	0.50	146	61.0	7.75	74.56	23.64	76.81

Mice weight=453.4 (g) Morning: NH_3 (tube)=108.5 ppm Afternoon: NH_3 (tube)=126

Room (desired RH 35-40 percent)								
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.7	0.16	9	-	-	68.30	20.17	42.99
2	20.7	0.14	16	-	-	69.69	20.94	41.28
3	20.6	0.13	22	-	-	69.88	21.04	41.90
Average	20.7	0.14	16			69.29	20.72	42.06
4	20.7	0.12	-	-	-	70.18	21.21	41.50
5	20.7	0.04	-	-	-	69.00	20.56	40.53
6	20.6	0.01	-	-	-	69.74	20.97	40.12
Average	20.7	0.06	-			69.64	20.91	40.72

Morning: NH_3 (tube)=0 ppm Afternoon: NH_3 (tube)=0 ppm

Date: DEC 21,1997 **Day:** 9
Barometric pressure: 29.79 (in) **Desired temperature:** 24+-1.5 °C
Desired temperature: 24+-1.5 °C

Cage: 1,2,3,4						Calorimeter – 2 (desired RH 30-35 percent)		
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.4	0.23	10	70.0	9.10	74.55	23.64	46.71
2	20.4	0.23	9	70.0	9.10	74.52	23.62	46.99
3	20.4	0.24	9	69.0	8.95	74.59	23.66	47.22
Average	20.4	0.23	9	69.7	9.05	74.55	23.64	46.97
4	20.3	0.36	27	68.0	8.80	74.75	23.75	49.99
5	20.2	0.42	47	68.0	8.80	74.85	23.81	51.47
6	20.3	0.33	54	68.0	8.80	74.66	23.70	50.36
Average	20.3	0.37	43	68.0	8.80	74.75	23.75	50.61

Mice weight=464.8 (g) Morning: NH_3 (tube)=8.5 ppm Afternoon: NH_3 (tube)=11 ppm

Cage: 5,6,7,8				Calorimeter – 3 (desired RH 75-80 percent)				
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.2	0.33	162	70.0	9.24	72.67	22.59	68.21
2	20.2	0.32	131	70.0	9.24	72.66	22.59	69.41
3	20.1	0.32	120	70.0	9.24	72.71	22.62	68.54
Average	20.2	0.32	138	70.0	9.24	72.68	22.60	68.72
4	20.2	0.39	140	70.0	9.24	72.63	22.57	74.63
5	20.1	0.38	156	70.0	9.24	72.54	22.52	75.06
6	20.2	0.39	158	70.0	9.24	72.64	22.58	75.93
Average	20.2	0.39	151	70.0	9.24	72.60	22.56	75.21

Mice weight=459.9 (g)] Morning: NH_3 (tube)=123.3 ppm Afternoon: NH_3 (tube)=125 ppm

Cage: 9,10,11,12				Calorimeter – 1 (desired RH 75-80 percent)				
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.2	0.31	115	70.0	9.34	72.37	22.43	78.69
2	20.3	0.31	122	69.0	9.18	72.19	22.33	80.24
3	20.1	0.31	118	69.0	9.18	72.23	22.35	78.16
Average	20.2	0.31	118	69.3	9.24	72.26	22.37	79.03
4	20.2	0.33	122	69.0	9.18	72.35	22.42	75.40
5	20.1	0.48	132	69.0	9.18	72.36	22.42	77.82
6	20.0	0.53	135	69.0	9.18	72.42	22.46	79.47
Average	20.1	0.45	130	69.0	9.18	72.38	22.43	77.56

Mice weight=460.2 (g) Morning: NH_3 (tube)=120 ppm Afternoon: NH_3 (tube)=145 ppm

Room (desired RH 35-40 percent)								
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.7	0.2	6	-	-	69.63	20.91	30.51
2	20.7	0.16	3	-	-	70.07	21.15	30.69
3	20.7	0.15	4	-	-	68.35	20.19	28.14
Average	20.7	0.17	4			69.35	20.75	29.78
4	20.7	0.15	40	-	-	69.87	21.04	30.97
5	20.7	0.14	54	-	-	69.87	21.04	31.33
6	20.7	0.15	58	-	-	68.90	20.50	32.33
Average	20.7	0.15	51			69.55	20.86	31.54

Morning: NH_3 (tube)=0 ppm Afternoon: NH_3 (tube)=0 ppm

Date: DEC 22,1997 **Day:** 10
Barometric pressure: 29.73 (in) **Desired temperature:** 24+-1.5 °C
Desired airflow: 5 (l/min)

Cage: 1,2,3,4					Calorimeter – 1 (desired RH 30-35 percent)			
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.3	0.23	7	69.0	9.18	72.66	22.59	50.33
2	20.3	0.17	25	69.0	9.18	72.49	22.49	50.14
3	20.4	0.38	30	69.0	9.18	72.50	22.50	44.51
Average	20.3	0.26	21	69.0	9.18	72.55	22.53	48.33
4	20.3	0.37	15	69.0	9.18	72.71	22.62	51.42
5	20.3	0.37	35	69.0	9.18	72.66	22.59	52.42
6	20.3	0.35	43	69.0	9.18	72.67	22.59	53.29
Average	20.3	0.36	31	69.0	9.18	72.68	22.60	52.38

Mice weight=471.8 (g) Morning: NH_3 (tube)=11.5 ppm Afternoon: NH_3 (tube)=12 ppm

Cage: 5,6,7,8					Calorimeter – 2 (desired RH 75-80 percent)			
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.3	0.28	117	68.0	8.80	74.40	23.56	78.20
2	20.1	0.27	127	68.0	8.80	74.98	23.88	81.17
3	20.1	0.56	145	68.0	8.80	74.80	23.78	80.38
Average	20.2	0.37	130	68.0	8.80	74.73	23.74	79.92
4	20.1	0.36	118	68.0	8.80	74.64	23.69	73.70
5	20.1	0.38	139	68.0	8.80	74.56	23.64	78.86
6	20.1	0.41	142	69.0	8.95	74.63	23.68	80.61
Average	20.1	0.38	133	68.3	8.85	74.61	23.67	77.72

Mice weight=463.7 (g) Morning: NH_3 (tube)=140ppm Afternoon: NH_3 (tube)=150 ppm

Cage: 9,10,11,12					Calorimeter - 3(desired RH 75-80 percent)			
	Concentration			Airflow		Act ual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.1	0.30	85	69.0	9.09	73.00	22.78	75.00
2	20.1	0.43	102	69.0	9.09	74.23	23.46	75.59
3	20.1	0.53	98	69.0	9.09	73.10	22.83	78.00
Average	20.1	0.42	95	69.0	9.09	73.44	23.02	76.20
4	20.1	0.51	98	69.0	9.09	72.83	22.68	80.27
5	20.0	0.43	121	69.0	9.09	72.81	22.67	81.15
6	20.1	0.40	128	69.0	9.09	72.85	22.69	81.68
Average	20.1	0.45	116	69.0	9.09	72.83	22.68	81.03

Mice weight=465.2 (g) Morning: NH_3 (tube)=86 ppm Afternoon: NH_3 (tube)=96 ppm

Room (desired RH 35-40 percent)								
	Concentration			Airflow		Actual temperature		
Time	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Scale	Rate (l/min)	Temp (°F)	Temp(°C)	Actual RH (percent)
1	20.6	0.13	17	-	-	68.40	20.22	42.90
2	20.6	0.02	34	-	-	68.54	20.30	42.31
3	20.6	0.17	43	-	-	69.90	21.06	41.00
Average	20.6	0.11	31			68.95	20.53	42.07
4	20.6	0.02	30	-	-	69.37	20.76	44.54
5	20.6	0.13	45	-	-	69.85	21.03	43.49
6	20.6	0.12	60	-	-	68.61	20.34	43.54
Average	20.6	0.09	45			69.28	20.71	43.86

Morning: NH_3 (tube)=0 ppm Afternoon: NH_3 (tube)=0 ppm

3.4.1.3 Individual Calorimeter Data (O_2 percent, CO_2 percent, and NH_3 ppm) for Test 1

For cages: 1,2,3,4

Desired temperature: 24+-1.5 °C **Desired humidity:** 30-35 percent

Lights on								
Day	**Calor.**	**O_2 (percent)**	**CO_2 (percent)**	**NH_3 (ppm)**	**Airflow (l/min)**	**Actual RH (percent)**	**Temp. (°C)**	**Bar. press (in)**
1	1	19.97	0.74	0	4.95	73.72	21.15	30.22
2	3	20.13	0.53	6	4.79	58.66	23.94	30.02
3	2	20.17	0.46	10	5.03	55.97	23.18	30.12
4	1	20.03	0.58	17	4.99	54.12	24.90	30.18
5	3	20.23	0.48	18	4.92	51.70	24.83	30.19
6	2	20.10	0.48	-	4.49	53.60	24.13	29.89
7	1	20.17	0.47	36	4.99	41.53	27.67	29.97
8	3	20.33	0.45	31	4.39	48.82	24.24	29.68
9	2	20.23	0.47	53	5.15	56.59	24.64	29.52
10	1	20.13	0.51	97	5.04	52.71	24.84	29.98

Light off								
Day	**Calor.**	**O_2 (percent)**	**CO_2 (percent)**	**NH_3 (ppm)**	**Airflow (l/min)**	**Actual RH (percent)**	**Temp. (°C)**	**Bar. press (in)**
1	1	19.97	0.76	8	5.17	71.33	21.39	30.22
2	3	20.00	0.64	10	5.04	66.06	22.66	30.02
3	2	20.00	0.66	15	5.03	70.40	24.19	30.12
4	1	19.93	0.81	23	4.99	62.91	24.77	30.18
5	3	20.13	0.70	0	4.89	61.39	24.52	30.19
6	2	20.00	0.64	26	4.89	54.44	25.50	29.89
7	1	19.93	0.82	38	4.99	52.63	26.30	29.97
8	3	20.17	0.85	37	4.95	58.43	24.02	29.68
9	2	20.20	0.56	83	5.10	61.41	24.47	29.52
10	1	20.10	0.65	112	5.06	57.12	25.16	29.98

For cages: 5,6,7,8

Desired temperature: 24+-1.5 °C **Desired humidity**: 75-80 percent

Lights on								
Day	**Calor.**	**O_2 (percent)**	**CO_2 (percent)**	**NH_3 (ppm)**	**Airflow (l/min)**	**Actual RH (percent)**	**Temp. (°C)**	**Bar. press (in)**
1	2	20.00	0.64	0	4.80	86.81	23.33	30.22
2	1	19.90	0.65	7	4.86	85.62	23.15	30.02
3	3	20.10	0.51	9	5.23	76.10	23.56	30.12
4	2	20.07	0.55	39	4.91	73.72	23.65	30.18
5	1	20.07	0.59	44	4.99	77.47	24.95	30.19
6	3	19.80	0.72	-	4.95	74.67	24.03	29.89
7	2	20.03	0.51	69	4.89	75.83	24.76	29.97
8	1	20.10	0.65	86	4.86	89.81	24.89	29.68
9	3	19.87	0.72	73	4.95	80.91	23.60	29.52
10	2	20.13	0.51	70	5.03	80.29	24.50	29.98

Light off								
Day	**Calor.**	**O_2 (percent)**	**CO_2 (percent)**	**NH_3 (ppm)**	**Airflow (l/min)**	**Actual RH (percent)**	**Temp. (°C)**	**Bar. press (in)**
1	2	20.03	0.68	7	4.76	69.67	23.48	30.22
2	1	19.77	0.72	10	4.86	84.76	21.03	30.02
3	3	19.97	0.71	26	5.13	83.76	22.94	30.12
4	2	20.07	0.67	71	4.91	78.25	24.72	30.18
5	1	19.87	0.82	76	4.99	77.69	25.30	30.19
6	3	19.97	0.82	79	5.13	79.59	25.13	29.89
7	2	20.07	0.67	104	4.89	76.26	24.59	29.97
8	1	20.17	0.78	140	5.17	81.09	-	29.68
9	3	20.07	0.79	133	4.95	83.45	23.89	29.52
10	2	20.10	0.59	101	5.03	80.65	24.51	29.98

For cages: 9,10,11,12
Desired temperature: 24+-1.5 °C **Desired humidity**: 30-35 percent

Lights on								
Day	**Calor.**	**O_2 (percent)**	**CO_2 (percent)**	**NH_3 (ppm)**	**Airflow (l/min)**	**Actual RH (percent)**	**Temp.(°C)**	**Bar. press (in)**
1	3	20.00	0.65	0	6.06	72.25	23.06	30.22
2	2	20.10	0.55	6	4.47	61.20	24.55	30.02
3	1	20.07	0.61	8	4.99	53.09	13.45	30.12
4	3	20.10	0.57	15	4.95	62.61	23.14	30.18
5	2	20.20	0.45	27	5.00	50.77	25.08	30.19
6	1	20.00	0.62	-	5.02	52.55	23.87	29.89
7	3	20.10	0.55	61	4.95	55.46	24.67	29.97
8	2	20.33	0.46	37	4.91	50.41	24.60	29.68
9	1	20.07	0.57	55	5.17	52.84	-	29.52
10	3	20.17	0.54	50	4.95	53.56	24.09	29.98

Light off								
Day	**Calor.**	**O_2 (percent)**	**CO_2 (percent)**	**NH_3 (ppm)**	**Airflow (l/min)**	**Actual RH (percent)**	**Temp. (°C)**	**Bar. press (in)**
1	3	20.10	0.72	8	6.55	68.00	23.46	30.22
2	2	19.90	0.66	10	5.03	67.68	24.73	30.02
3	1	19.90	0.83	13	4.93	62.84	15.91	30.12
4	3	20.17	0.67	24	4.92	66.18	24.01	30.18
5	2	20.00	0.59	25	4.96	56.84	24.84	30.19
6	1	20.00	0.75	32	4.99	55.54	24.70	29.89
7	3	20.00	0.82	53	4.95	62.36	23.96	29.97
8	2	20.30	0.61	41	5.07	54.11	24.67	29.68
9	1	20.10	0.74	98	4.99	60.18	25.02	29.52
10	3	20.13	0.71	73	4.95	60.45	24.03	29.98

For room
Desired temperature: 24+-1.5 °C **Desired humidity**: 35-40 percent

Lights on								
Day	**Calor.**	**O_2 (percent)**	**CO_2 (percent)**	**NH_3 (ppm)**	**Airflow (l/min)**	**Actual RH (percent)**	**Temp. (°C)**	**Bar. press (in)**
1	-	20.63	0.06	0	-	35.29	19.02	30.22
2	-	20.47	0.09	7	-	36.70	21.42	30.02
3	-	20.67	0.07	10	-	46.82	19.05	30.12
4	-	20.57	0.06	16	-	42.05	21.62	30.18
5	-	20.43	0.06	16	-	31.70	22.09	30.19
6	-	20.60	0.05		-	40.86	18.59	29.89
7	-	20.70	0.05	11	-	32.08	21.96	29.97
8	-	20.60	0.09	4	-	41.48	21.42	29.68
9	-	20.57	0.10	6	-	40.44	21.55	29.52
10	-	20.60	0.07	12	-	40.07	21.75	29.98

Light off								
Day	Calor.	O_2 (percent)	CO_2 (percent)	NH_3 (ppm)	Airflow (l/min)	Actual RH (percent)	Temp. (°C)	Bar. press (in)
1	-	20.67	0.06	9	-	37.67	19.50	30.22
2	-	20.45	0.09	9	-	38.08	21.19	30.02
3	-	20.50	0.09	14	-	46.26	20.72	30.12
4	-	20.53	0.09	26	-	35.12	23.17	30.18
5	-	20.30	0.06	8	-	35.25	22.46	30.19
6	-	20.20	0.07	0	-	32.18	23.17	29.89
7	-	20.70	0.07	1	-	43.99	21.21	29.97
8	-	20.97	0.05	0	-	41.55	21.65	29.68
9	-	20.70	0.10	14	-	41.47	21.37	29.52
10	-	20.70	0.06	9	-	38.91	21.43	29.98

For cages: 1,2,3,4
Desired temperature: 24+-1.5 °C **Desired humidity**: 30-35 percent

Light on			Generation rate			
Day	O_2 (l/min)	CO_2 (l/min)	CO_2 (g/hr/100g bw)	NH_3 (g/hr/100g)	Max NH_3 (g/hr/100g)	Mice wt (g)
1	-3.30E-02	3.38E-02	9.92E-01	-1.87E-05	0.00E+00	401.6
2	-1.60E-02	2.08E-02	6.00E-01	3.21E-04	5.36E-04	408.0
3	-2.51E-02	1.98E-02	5.63E-01	5.53E-04	6.64E-04	413.9
4	-2.66E-02	2.61E-02	7.33E-01	9.39E-04	1.19E-03	420.3
5	-9.84E-03	2.10E-02	5.76E-01	9.40E-04	1.15E-03	429.5
6	-2.25E-02	1.92E-02	5.17E-01	-	-	437.1
7	-2.66E-02	2.10E-02	5.60E-01	1.84E-03	2.06E-03	441.1
8	-1.17E-02	1.58E-02	4.14E-01	1.40E-03	1.47E-03	449.9
9	-1.72E-02	1.89E-02	4.94E-01	2.76E-03	2.92E-03	449.7
10	-2.35E-02	2.22E-02	5.69E-01	4.83E-03	5.00E-03	459.4

Light off			Generation rate			
Day	O_2 (l/min)	CO_2 (l/min)	CO_2 (g/hr/100g bw)	NH_3 (g/hr/100g)	Max NH_3 (g/hr/100g)	Mice wt (g)
1	-3.62E-02	3.62E-02	1.06E+00	4.69E-04	5.87E-04	401.6
2	-2.28E-02	2.78E-02	8.02E-01	5.44E-04	7.32E-04	408.0
3	-2.51E-02	2.88E-02	8.20E-01	8.30E-04	9.96E-04	413.9
4	-3.00E-02	3.61E-02	1.01E+00	1.26E-03	1.52E-03	420.3
5	-8.15E-03	3.11E-02	8.54E-01	0.00E+00	2.07E-04	429.5
6	-9.78E-03	2.79E-02	7.52E-01	1.34E-03	1.38E-03	437.1
7	-3.83E-02	3.75E-02	1.00E+00	1.96E-03	2.22E-03	441.1
8	-3.96E-02	3.93E-02	1.03E+00	1.86E-03	2.06E-03	449.9
9	-2.55E-02	2.31E-02	6.06E-01	4.31E-03	4.55E-03	449.7
10	-3.04E-02	2.97E-02	7.61E-01	5.62E-03	6.28E-03	459.4

For cages: 5,6,7,8
Desired temperature: 24+-1.5 °C **Desired humidity**: 75-80 percent

Light on			Generation rate			
Day	O_2 (l/min)	CO_2 (l/min)	CO_2 (g/hr/100g bw)	NH_3 (g/hr/100g)	Max NH_3 (g/hr/100g)	Mice wt (g)
1	-3.04E-02	2.80E-02	8.06E-01	1.78E-05	1.07E-04	409.8
2	-2.76E-02	2.69E-02	7.73E-01	3.78E-04	6.49E-04	410.1
3	-2.96E-02	2.33E-02	6.59E-01	4.95E-04	6.28E-04	417.5
4	-2.46E-02	2.41E-02	6.68E-01	2.04E-03	2.48E-03	424.7
5	-1.83E-02	2.66E-02	7.34E-01	2.34E-03	2.55E-03	427.8
6	-3.96E-02	3.30E-02	8.97E-01	-	-	433.2
7	-3.26E-02	2.25E-02	5.99E-01	3.49E-03	3.58E-03	442.8
8	-2.43E-02	2.72E-02	7.14E-01	4.26E-03	4.44E-03	449.4
9	-3.46E-02	3.08E-02	7.99E-01	3.61E-03	3.67E-03	454.7
10	-2.35E-02	2.21E-02	5.65E-01	3.46E-03	3.53E-03	461.1

Light off			Generation rate			
Day	O_2 (l/min)	CO_2 (l/min)	CO_2 (g/hr/100g bw)	NH_3 (g/hr/100g)	Max NH_3 (g/hr/100g)	Mice wt (g)
1	-3.01E-02	2.95E-02	8.48E-01	3.88E-04	4.76E-04	409.8
2	-3.33E-02	3.07E-02	8.82E-01	5.23E-04	6.49E-04	410.1
3	-2.74E-02	3.18E-02	8.98E-01	1.46E-03	1.91E-03	417.5
4	-2.29E-02	2.83E-02	7.86E-01	3.73E-03	4.11E-03	424.7
5	-2.16E-02	3.78E-02	1.04E+00	4.06E-03	4.68E-03	427.8
6	-1.20E-02	3.87E-02	1.05E+00	4.27E-03	4.48E-03	433.2
7	-3.10E-02	2.95E-02	7.85E-01	5.22E-03	5.39E-03	442.8
8	-4.13E-02	3.77E-02	9.89E-01	7.30E-03	7.65E-03	449.4
9	-3.13E-02	3.41E-02	8.85E-01	6.60E-03	6.70E-03	454.7
10	-3.02E-02	2.65E-02	6.76E-01	5.02E-03	5.22E-03	461.1

For cages: 9,10,11,12
Desired temperature: 24+-1.5 °C **Desired humidity**: 30-35 percent

Light on			Generation rate			
Day	**O_2 (l/min)**	**CO_2 (l/min)**	**CO_2 (g/hr/100g bw)**	**NH_3 (g/hr/100g)**	**Max NH_3 (g/hr/100g)**	**Mice wt (g)**
1	-3.84E-02	3.57E-02	1.00E+00	0.00E+00	6.56E-05	421.0
2	-1.64E-02	2.03E-02	5.65E-01	3.05E-04	5.30E-04	422.7
3	-3.00E-02	2.70E-02	7.42E-01	3.99E-04	5.32E-04	428.3
4	-2.31E-02	2.52E-02	6.80E-01	7.57E-04	1.08E-03	437.1
5	-1.17E-02	1.97E-02	5.21E-01	1.37E-03	1.59E-03	445.5
6	-3.01E-02	2.86E-02	7.42E-01	-	-	454.1
7	-2.97E-02	2.46E-02	6.28E-01	2.97E-03	3.28E-03	461.2
8	-1.31E-02	1.80E-02	4.57E-01	1.79E-03	1.83E-03	464.1
9	-2.58E-02	2.45E-02	6.11E-01	2.73E-03	2.80E-03	471.9
10	-2.14E-02	2.33E-02	5.73E-01	2.34E-03	2.55E-03	478.3

Light off			Generation rate			
Day	**O_2 (l/min)**	**CO_2 (l/min)**	**CO_2 (g/hr/100g bw)**	**NH_3 (g/hr/100g)**	**Max NH_3 (g/hr/100g)**	**Mice wt (g)**
1	-3.71E-02	4.34E-02	1.22E+00	5.67E-04	6.38E-04	421.0
2	-2.78E-02	2.85E-02	7.95E-01	5.24E-04	7.59E-04	422.7
3	-2.96E-02	3.63E-02	9.99E-01	6.99E-04	8.39E-04	428.3
4	-1.80E-02	2.85E-02	7.69E-01	1.23E-03	1.44E-03	437.1
5	-1.49E-02	2.63E-02	6.95E-01	1.29E-03	1.42E-03	445.5
6	-9.99E-03	3.41E-02	8.85E-01	1.59E-03	1.65E-03	454.1
7	-3.46E-02	3.69E-02	9.44E-01	2.59E-03	2.69E-03	461.2
8	-3.38E-02	2.81E-02	7.12E-01	2.04E-03	2.24E-03	464.1
9	-3.00E-02	3.20E-02	7.98E-01	4.71E-03	4.78E-03	471.9
10	-2.80E-02	3.23E-02	7.97E-01	3.43E-03	4.01E-03	478.3

3.4.1.4 Individual Calorimeter Data (O_2 percent, CO_2 percent, and NH_3 ppm) for Test 2

For cages: 1,2,3,4
Desired temperature: 24+-1.5 °C **Desired humidity:** 30-35 percent

Lights on										
Day	**Calor.**	**O_2 (percent)**	**CO_2 (percent)**	**Tube NH_3 (ppm)**	**NH_3 (ppm)**	**Max NH_3 (ppm)**	**Airflow (l/min)**	**Actual RH (percent)**	**Temp. (°C)**	**Bar. press (in)**
1	1	20.17	0.63	0	0	0	4.98	67.24	22.23	29.77
2	3	19.97	0.62	0	3	3	4.99	60.60	23.31	29.77
3	2	20.10	0.55	0	2	2	5.01	54.46	24.80	29.83
4	1	20.10	0.55	1	2	2	4.92	57.10	24.88	30.06
5	3	20.07	-	1	10	11	5.08	60.47	24.21	30.04
6	2	20.00	0.52	4	15	18	4.89	51.85	26.09	29.83
7	1	20.10	0.50	2	10	10	5.93	54.42	24.05	29.72
8	3	20.30	0.30	2	21	28	7.71	46.63	22.85	29.92
9	2	20.40	0.23	9	9	10	9.05	46.97	23.64	29.79
10	1	20.33	0.26	12	21	30	9.18	48.33	22.53	29.72

Light off										
Day	**Calor.**	**O_2 (percent)**	**CO_2 (percent)**	**Tube NH_3 (ppm)**	**NH_3 (ppm)**	**Max NH_3 (ppm)**	**Airflow (l/min)**	**Actual RH (percent)**	**Temp. (°C)**	**Bar. press (in)**
1	1	20.00	0.74	0	2	2	4.99	69.74	22.26	29.77
2	3	19.93	0.76	0	0	0	4.97	59.57	23.56	29.77
3	2	19.93	0.77	0	1	2	4.96	62.64	24.95	29.86
4	1	19.90	0.80	1	6	6	4.89	63.70	25.14	29.82
5	3	19.70	0.62	2	11	12	5.08	64.44	23.81	30.04
6	2	19.80	0.66	5	21	22	4.92	57.95	24.82	29.80
7	1	20.03	0.72	2	17	24	5.83	64.04	23.35	29.83
8	3	20.23	0.47	5	-	-	7.74	50.30	22.93	29.92
9	2	20.27	0.37	11	43	54	8.80	50.61	23.75	29.79
10	1	20.30	0.36	12	31	43	9.18	52.38	22.60	29.74

For cages: 5,6,7,8

Desired temperature: 24+-1.5 °C **Desired humidity: 75-80 percent**

Lights on										
Day	Calor.	O_2 (percent)	CO_2 (percent)	Tube NH_3 (ppm)	NH_3 (ppm)	Max NH_3 (ppm)	Airflow (l/min)	Actual RH (percent)	Temp. (°C)	Bar. press (in)
1	2	20.07	0.64	1	1	1	5.04	75.50	23.07	29.77
2	1	20.00	0.65	0	3	3	4.99	81.77	22.49	29.77
3	3	19.97	0.61	1	2	3	5.16	74.72	23.30	29.83
4	2	19.97	0.59	2	2	2	4.98	78.84	24.57	30.06
5	1	20.00	-	21	14	19	4.99	78.00	23.82	30.04
6	3	19.90	0.50	85	80	84	5.11	73.49	23.88	29.83
7	2	20.13	0.46	84	88	89	6.19	81.90	24.75	29.72
8	1	20.17	0.35	104	121	123	7.88	77.32	22.52	29.92
9	3	20.17	0.32	123	138	162	9.24	68.72	22.60	29.79
10	2	20.17	0.37	140	130	145	8.80	79.92	23.74	29.72

Light off										
Day	Calor.	O_2 (percent)	CO_2 (percent)	Tube NH_3 (ppm)	NH_3 (ppm)	Max NH_3 (ppm)	Airflow (l/min)	Actual RH (percent)	Temp. (°C)	Bar. press (in)
1	2	19.93	0.70	0	2	3	4.99	73.94	22.98	29.77
2	1	19.67	0.79	0	1	1	5.04	83.50	22.84	29.77
3	3	19.97	0.76	0	2	2	5.05	79.49	23.96	29.86
4	2	19.93	0.73	8	7	8	4.96	83.82	24.49	29.82
5	1	19.63	0.71	46	41	42	5.04	86.86	24.21	30.04
6	3	19.87	0.67	90	127	135	5.19	75.74	24.21	29.80
7	2	19.90	0.74	110	135	147	5.94	87.53	24.44	29.83
8	1	20.07	0.51	126	127	132	7.82	77.27	22.54	29.92
9	3	20.17	0.39	125	151	158	9.24	75.21	22.56	29.79
10	2	20.10	0.38	150	133	139	8.85	77.72	23.67	29.74

For cages: 9,10,11,12
Desired temperature: 24+-1.5 °C **Desired humidity: 75-80 percent**

Lights on										
Day	Calor.	O_2 (percent)	CO_2 (percent)	Tube NH_3 (ppm)	NH_3 (ppm)	Max NH_3 (ppm)	Airflow (l/min)	Actual RH (percent)	Temp. (°C)	Bar. press (in)
1	3	20.07	0.67	0	0	0	4.99	73.03	22.90	29.77
2	2	20.20	0.63	0	4	4	5.02	83.00	23.09	29.77
3	1	20.07	0.62	0	2	2	4.97	82.87	24.72	29.83
4	3	20.00	0.60	8	2	3	5.11	74.05	23.69	30.06
5	2	19.93	-	57	43	47	5.09	77.25	24.69	30.04
6	1	19.87	0.47	90	105	109	5.03	75.79	24.96	29.83
7	3	20.03	0.54	86	89	92	6.03	72.58	23.92	29.72
8	2	20.10	0.33	109	139	142	7.64	78.55	23.72	29.92
9	1	20.20	0.31	120	118	122	9.24	79.03	22.37	29.79
10	3	20.10	0.42	86	95	102	9.09	76.20	23.02	29.72

Light off										
Day	Calor.	O_2 (percent)	CO_2 (percent)	Tube NH_3 (ppm)	NH_3 (ppm)	Max NH_3 (ppm)	Airflow (l/min)	Actual RH (percent)	Temp. (°C)	Bar. press (in)
1	3	19.93	0.75	0	2	3	4.91	74.26	23.01	29.77
2	2	19.73	0.73	0	1	1	4.88	80.43	23.49	29.77
3	1	19.83	0.88	0	1	2	4.89	84.37	25.41	29.86
4	3	19.73	0.83	10	10	12	5.03	79.44	23.72	29.82
5	2	19.67	0.68	76	65	69	4.96	82.81	24.82	30.04
6	1	19.80	0.75	105	125	132	5.03	81.10	24.13	29.80
7	3	19.90	0.74	105	147	153	6.03	76.52	23.66	29.83
8	2	20.03	0.50	126	146	153	7.75	76.81	23.64	29.92
9	1	20.10	0.45	145	130	135	9.18	77.56	22.43	29.79
10	3	20.07	0.45	96	116	128	9.09	81.03	22.68	29.74

For room

Desired temperature: 24+-1.5 °C Desired humidity: 35-40 percent

Lights on										
Day	**Calor.**	**O_2 (percent)**	**CO_2 (percent)**	**Tube NH_3 (ppm)**	**NH_3 (ppm)**	**Max NH_3 (ppm)**	**Airflow (l/min)**	**Actual RH (percent)**	**Temp. (°C)**	**Bar. press (in)**
1	-	20.73	0.03	0	-1	0	-	38.10	18.54	29.77
2	-	20.73	0.06	0	3	3	-	37.30	19.29	29.77
3	-	20.60	0.04	0	2	2	-	35.84	21.09	29.83
4	-	20.70	0.06	0	2	2	-	36.06	20.79	30.06
5	-	20.77	-	0	5	7	-	36.99	21.49	30.04
6	-	20.50	0.06	0	15	17	-	38.10	18.54	29.83
7	-	20.73	0.06	0	3	3	-	37.30	19.29	29.72
8	-	20.67	0.03	0	16	22	-	42.06	20.72	29.92
9	-	20.70	0.03	0	4	6	-	29.78	20.75	29.79
10	-	20.60	0.03	0	31	43	-	42.07	20.53	29.72

Light off										
Day	**Calor.**	**O_2 (percent)**	**CO_2 (percent)**	**Tube NH_3 (ppm)**	**NH_3 (ppm)**	**Max NH_3 (ppm)**	**Airflow (l/min)**	**Actual RH (percent)**	**Temp. (°C)**	**Bar. press (in)**
1	-	20.80	0.05	0	3	3	-	39.47	18.58	29.77
2	-	20.60	0.05	0	1	1	-	38.03	19.67	29.77
3	-	20.70	0.06	0	2	2	-	35.71	21.47	29.86
4	-	20.67	0.06	0	6	7	-	37.99	20.76	29.82
5	-	20.60	0.04	0	8	9	-	39.77	20.06	30.04
6	-	20.50	0.04	0	23	24	-	39.47	18.58	29.80
7	-	20.60	0.05	0	1	1	-	38.03	19.67	29.83
8	-	20.67	0.03	0	-	-	-	40.72	20.91	29.92
9	-	20.70	0.03	0	51	135	-	31.54	20.86	29.79
10	-	20.60	0.03	0	45	60	-	43.86	20.71	29.74

For cages: 1,2,3,4 a. data based on calorimetric tube. b. data based on PhD meter
Desired temperature: 24+-1.5 °C Desired humidity: 30-35 percent

Light on				Generation rate			
Day	O_2 (l/min)	CO_2 (l/min)	CO_2 (g/hr/100g)	Tube NH_3 [a] (g/hr/100g)	NH_3 [b] (g/hr/100g)	Max NH_3 (g/hr/100g)	Mice wt (g)
1	-2.81E-02	2.97E-02	8.51E-01	0.00E+00	-1.84E-05	0.00E+00	411.7
2	-3.81E-02	2.79E-02	7.89E-01	0.00E+00	1.63E-04	1.63E-04	417.1
3	-2.50E-02	2.54E-02	7.01E-01	0.00E+00	8.91E-05	1.07E-04	426.9
4	-2.95E-02	2.43E-02	6.54E-01	5.13E-05	1.03E-04	1.03E-04	437.4
5	-3.57E-02	-	-	5.24E-05	5.07E-04	5.76E-04	442.0
6	-2.45E-02	2.23E-02	5.89E-01	2.00E-04	7.65E-04	8.98E-04	447.1
7	-3.74E-02	2.59E-02	6.74E-01	1.19E-04	5.97E-04	5.97E-04	453.0
8	-2.85E-02	2.06E-02	5.28E-01	1.53E-04	1.58E-03	2.14E-03	459.2
9	-2.71E-02	1.84E-02	4.66E-01	7.54E-04	8.28E-04	8.87E-04	464.8
10	-2.45E-02	2.11E-02	5.28E-01	1.02E-03	1.83E-03	2.66E-03	471.8

Light off				Generation rate			
Day	O_2 (l/min)	CO_2 (l/min)	CO_2 (g/hr/100g)	Tube NH_3 [a] (g/hr/100g)	NH_3 [b] (g/hr/100g)	Max NH_3 (g/hr/100g)	Mice wt (g)
1	-3.99E-02	3.45E-02	9.86E-01	0.00E+00	9.21E-05	1.11E-04	411.7
2	-3.31E-02	3.51E-02	9.92E-01	0.00E+00	0.00E+00	0.00E+00	417.1
3	-3.80E-02	3.54E-02	9.76E-01	0.00E+00	5.30E-05	1.06E-04	426.9
4	-3.77E-02	3.60E-02	9.71E-01	5.10E-05	2.89E-04	3.06E-04	437.4
5	-4.57E-02	2.96E-02	7.90E-01	7.86E-05	5.94E-04	6.29E-04	442.0
6	-3.44E-02	3.05E-02	8.04E-01	2.51E-04	1.05E-03	1.10E-03	447.1
7	-3.30E-02	3.92E-02	1.02E+00	1.17E-04	1.02E-03	1.41E-03	453.0
8	-3.38E-02	3.43E-02	8.80E-01	3.84E-04	-	-	459.2
9	-3.81E-02	2.99E-02	7.58E-01	9.49E-04	3.68E-03	4.66E-03	464.8
10	-2.75E-02	3.06E-02	7.65E-01	1.06E-03	2.75E-03	3.82E-03	471.8

For cages: 5,6,7,8 **a. data based on calorimetric tube. b. data based on PhD meter.**
Desired temperature: 24+-1.5 °C **Desired humidity: 75-80 percent**

Light on				Generation rate			
Day	O_2 (l/min)	CO_2 (l/min)	CO_2 (g/hr/100g)	Tube NH_3 [a] (g/hr/100g)	NH_3 [b] (g/hr/100g)	Max NH_3 (g/hr/100g)	Mice wt (g)
1	-3.34E-02	3.07E-02	8.71E-01	5.52E-05	3.68E-05	5.52E-05	415.9
2	-3.65E-02	2.93E-02	8.31E-01	0.00E+00	1.64E-04	1.64E-04	415.2
3	-3.27E-02	2.96E-02	8.34E-01	0.00E+00	1.13E-04	1.69E-04	418.1
4	-3.66E-02	2.66E-02	7.33E-01	7.98E-05	1.06E-04	1.06E-04	427.1
5	-3.84E-02	-	-	1.10E-03	7.51E-04	9.96E-04	434.2
6	-3.07E-02	2.27E-02	6.01E-01	4.46E-03	4.22E-03	4.41E-03	444.1
7	-3.70E-02	2.46E-02	6.47E-01	5.30E-03	5.54E-03	5.62E-03	447.2
8	-3.97E-02	2.55E-02	6.62E-01	8.24E-03	9.56E-03	9.74E-03	453.5
9	-4.93E-02	2.71E-02	6.95E-01	1.13E-02	1.26E-02	1.48E-02	459.9
10	-3.81E-02	2.99E-02	7.60E-01	1.21E-02	1.12E-02	1.25E-02	463.7

Light off				Generation rate			
Day	O_2 (l/min)	CO_2 (l/min)	CO_2 (g/hr/100g)	Tube NH_3 [a] (g/hr/100g)	NH_3 [b] (g/hr/100g)	Max NH_3 (g/hr/100g)	Mice wt (g)
1	-4.33E-02	3.25E-02	9.20E-01	0.00E+00	1.28E-04	1.64E-04	415.9
2	-4.70E-02	3.73E-02	1.06E+00	0.00E+00	3.69E-05	5.53E-05	415.2
3	-3.71E-02	3.55E-02	1.00E+00	0.00E+00	9.19E-05	1.10E-04	418.1
4	-3.65E-02	3.31E-02	9.12E-01	4.24E-04	3.71E-04	4.24E-04	427.1
5	-4.88E-02	3.40E-02	9.22E-01	2.44E-03	2.15E-03	2.22E-03	434.2
6	-3.29E-02	3.25E-02	8.63E-01	4.79E-03	6.75E-03	7.19E-03	444.1
7	-4.16E-02	4.08E-02	1.08E+00	6.67E-03	8.16E-03	8.91E-03	447.2
8	-4.72E-02	3.76E-02	9.76E-01	9.91E-03	1.00E-02	1.04E-02	453.5
9	-4.93E-02	3.30E-02	8.45E-01	1.15E-02	1.39E-02	1.45E-02	459.9
10	-4.42E-02	3.13E-02	7.94E-01	1.30E-02	1.16E-02	1.21E-02	463.7

For cages: 9,10,11,12 a. data based on calorimetric tube. b. data based on PhD meter.

Desired temperature: 24+-1.5 °C Desired humidity: 75-80 percent

Light on				Generation rate			
Day	O_2 (l/min)	CO_2 (l/min)	CO_2 (g/hr/100g)	Tube NH_3 [a] (g/hr/100g)	NH_3 [b] (g/hr/100g)	Max NH_3 (g/hr/100g)	Mice wt (g)
1	-3.31E-02	3.21E-02	9.09E-01	0.00E+00	0.00E+00	0.00E+00	415.9
2	-2.66E-02	2.86E-02	8.02E-01	0.00E+00	1.99E-04	2.18E-04	420.6
3	-2.65E-02	2.86E-02	7.95E-01	0.00E+00	8.88E-05	1.07E-04	424.9
4	-3.58E-02	2.76E-02	7.51E-01	4.30E-04	1.25E-04	1.61E-04	433.0
5	-4.26E-02	-	-	3.00E-03	2.24E-03	2.47E-03	441.2
6	-3.18E-02	2.08E-02	5.46E-01	4.60E-03	5.38E-03	5.57E-03	448.8
7	-4.20E-02	2.87E-02	7.54E-01	5.26E-03	5.47E-03	5.63E-03	449.3
8	-4.36E-02	2.29E-02	5.96E-01	8.34E-03	1.07E-02	1.09E-02	453.4
9	-4.62E-02	2.59E-02	6.62E-01	1.10E-02	1.08E-02	1.12E-02	460.2
10	-4.54E-02	3.54E-02	8.98E-01	7.66E-03	8.46E-03	9.09E-03	465.2

Light off				Generation rate			
Day	O_2 (l/min)	CO_2 (l/min)	CO_2 (g/hr/100g)	Tube NH_3 [a] (g/hr/100g)	NH_3 [b] (g/hr/100g)	Max NH_3 (g/hr/100g)	Mice wt (g)
1	-4.26E-02	3.45E-02	9.79E-01	0.00E+00	1.26E-04	1.61E-04	415.9
2	-4.23E-02	3.32E-02	9.30E-01	0.00E+00	3.53E-05	5.29E-05	420.6
3	-4.24E-02	4.01E-02	1.11E+00	0.00E+00	7.00E-05	1.05E-04	424.9
4	-4.71E-02	3.89E-02	1.06E+00	5.29E-04	5.29E-04	6.35E-04	433.0
5	-4.63E-02	3.17E-02	8.48E-01	3.89E-03	3.35E-03	3.54E-03	441.2
6	-3.52E-02	3.57E-02	9.37E-01	5.36E-03	6.38E-03	6.74E-03	448.8
7	-4.22E-02	4.16E-02	1.09E+00	6.42E-03	8.99E-03	9.36E-03	449.3
8	-4.93E-02	3.67E-02	9.53E-01	9.81E-03	1.14E-02	1.19E-02	453.4
9	-5.51E-02	3.83E-02	9.80E-01	1.32E-02	1.18E-02	1.23E-02	460.2
10	-4.85E-02	3.79E-02	9.59E-01	8.55E-03	1.03E-02	1.14E-02	465.2

3.4.1.5 Water Production Data: Data Used for Calculating Water Production for Test 1

For cages: 1,2,3,4
Desired temperature: 24+-1.5 C Desired humidity: 30-35 percent

Day	Average RH (percent)	Room RH (percent)	Actual T (°C)	Room T (°C)	Actual[1] (g/kg)	Room[2] (g/kg)	Airflow[3] (l/min)	Dried airflow[4] (l/min)	Mice wt (g)
1	55.30	36.45	21.27	19.26	8.75	5.00	5.06	2.28	401.6
2	53.07	36.77	23.30	21.30	9.50	5.50	4.92	0.73	408.0
3	53.95	47.03	23.68	19.89	9.75	6.75	5.03	1.08	413.9
4	47.22	41.31	24.83	22.40	9.25	7.00	4.99	0.97	420.3
5	47.05	34.15	24.68	22.27	9.00	5.75	4.90	0.75	429.5
6	48.75	38.07	24.82	20.88	9.40	5.75	4.69	1.07	437.1
7	39.90	35.67	26.98	21.59	9.00	5.75	4.99	1.46	441.1
8	46.72	40.66	24.13	21.54	8.50	6.75	4.67	0.87	449.9
9	53.43	39.85	24.56	21.46	10.25	6.25	5.12	1.04	449.7
10	46.36	38.93	25.00	21.59	9.00	6.25	5.05	0.61	459.4

For cages: 5,6,7,8
Desired temperature: 24+-1.5 C Desired humidity: 75-80 percent

Day	Average RH (percent)	Room RH (percent)	Actual T (°C)	Room T (°C)	Actual[1] (g/kg)	Room[2] (g/kg)	Airflow[3] (l/min)	Dried airflow[4] (l/min)	Mice wt (g)
1	71.98	36.45	23.41	19.26	13.00	5.00	4.78	1.27	409.8
2	77.34	36.77	22.09	21.30	12.75	5.50	4.86	2.26	410.1
3	76.67	47.03	23.25	19.89	13.5	6.75	5.18	0.19	417.5
4	71.30	41.31	24.19	22.40	13.25	7.00	4.91	1.22	424.7
5	77.28	34.15	25.13	22.27	15.25	5.75	4.99	1.36	427.8
6	74.11	38.07	24.58	20.88	14.75	5.75	5.04	0.88	433.2
7	76.78	35.67	24.68	21.59	14.75	5.75	4.89	0.90	442.8
8	79.46	40.66	24.89	21.54	15.75	6.75	5.02	0.61	449.4
9	75.20	39.85	23.75	21.46	14.00	6.25	4.95	0.81	454.7
10	73.22	38.93	24.51	21.59	14.25	6.25	5.03	1.15	461.1

For cages: 9,10,11,12
Desired temperature: 24+-1.5 °C Desired humidity: 30-35 percent

Day	Average RH (percent)	Room RH (percent)	Actual T (°C)	Room T (°C)	Actual[1] (g/kg)	Room[2] (g/kg)	Airflow[3] (l/min)	Dried airflow[4] (l/min)	Mice wt (g)
1	57.77	36.45	23.26	19.26	10.5	5.00	6.30	0.95	421
2	56.10	36.77	24.64	21.30	10.75	5.50	4.75	0.81	422.7
3	49.21	47.03	14.68	19.89	5.00	6.75	4.96	2.37	428.3
4	55.95	41.31	23.57	22.40	10.00	7.00	4.93	-	437.1
5	50.01	34.15	24.96	22.27	10.00	5.75	4.98	1.24	445.5
6	46.66	38.07	24.28	20.88	8.75	5.75	5.00	1.73	454.1
7	49.72	35.67	24.31	21.59	9.50	5.75	4.95	0.86	461.2
8	47.54	40.66	24.63	21.54	9.25	6.75	4.99	1.22	464.1
9	48.03	39.85	25.02	21.46	9.50	6.25	5.08	0.76	471.9
10	47.88	38.93	24.06	21.59	9.00	6.25	4.95	0.78	478.3

1. Humidity ratio (w) grams moisture per kilogram dry air for calorimeter
2. Humidity ratio (w) grams moisture per kilogram dry air for chamber
3. Total measured fresh air exchange rate for calorimeter
4. Portion of fresh air that passed through a column of desiccant

Water Production Data for Test 1

For cages: 1,2,3,4
Desired temperature: 24+-1.5 C Desired humidity: 30-35 percent

Day	Water from air in (g/hr/100g bw)	Water from air out (g/hr/100g bw)	Water from drierite (g/hr/100g bw)	Water added (g/hr/100 bw)	Total water (g/hr/100g bw)
1	2.41E-01	7.68E-01	6.92E-01	-	1.22E+00
2	3.93E-01	7.98E-01	6.76E-01	-	1.08E+00
3	4.49E-01	8.25E-01	5.70E-01	-	9.46E-01
4	4.67E-01	7.66E-01	5.26E-01	-	8.24E-01
5	3.87E-01	7.16E-01	4.56E-01	-	7.85E-01
6	3.32E-01	7.03E-01	4.83E-01	-	8.54E-01
7	3.21E-01	7.10E-01	4.19E-01	-	8.08E-01
8	3.98E-01	6.15E-01	4.91E-01	-	7.09E-01
9	3.95E-01	8.14E-01	2.78E-01	-	6.97E-01
10	4.20E-01	6.89E-01	4.61E-01	-	7.30E-01

For cages: 5,6,7,8
Desired temperature: 24+-1.5 C Desired humidity: 75-80 percent

Day	Water from air in (g/hr/100g bw)	Water from air out (g/hr/100g bw)	Water from drierite (g/hr/100g bw)	Water added (g/hr/100g bw)	Total water (g/hr/100g bw)
1	2.98E-01	1.06E+00	1.78E-01	1.54E+00	-6.01E-01
2	2.43E-01	1.05E+00	6.22E-01	2.93E-01	1.14E+00
3	5.62E-01	1.17E+00	1.87E-01	0.00E+00	7.92E-01
4	4.25E-01	1.07E+00	1.77E-01	0.00E+00	8.20E-01
5	3.40E-01	1.24E+00	4.68E-03	3.74E-01	5.31E-01
6	3.85E-01	1.20E+00	9.70E-02	0.00E+00	9.08E-01
7	3.61E-01	1.14E+00	6.10E-02	2.60E-01	5.75E-01
8	4.61E-01	1.22E+00	4.78E-01	4.67E-01	7.75E-01
9	3.96E-01	1.06E+00	4.18E-01	2.64E-01	8.20E-01
10	3.66E-01	1.08E+00	3.73E-01	0.00E+00	1.09E+00

For cages: 9,10,11,12
Desired temperature: 24+-1.5 °C Desired humidity: 30-35 percent

Day	Water from air in (g/hr/100g bw)	Water from air out (g/hr/100g bw)	Water from drierite (g/hr/100g bw)	Water added (g/hr/100 bw)	Total water (g/hr/100g bw)
1	4.43E-01	1.10E+00	8.31E-01	-	1.48E+00
2	3.57E-01	8.41E-01	6.01E-01	-	1.09E+00
3	2.85E-01	4.04E-01	7.70E-01	-	8.89E-01
4	5.51E-01	7.86E-01	6.13E-01	-	8.49E-01
5	3.36E-01	7.79E-01	7.30E-01	-	1.17E+00
6	2.89E-01	6.72E-01	4.76E-01	-	8.58E-01
7	3.55E-01	7.10E-01	4.71E-01	-	8.26E-01
8	3.82E-01	6.93E-01	4.29E-01	-	7.40E-01
9	3.99E-01	7.13E-01	2.69E-01	-	5.83E-01
10	3.80E-01	6.49E-01	4.75E-01	-	7.44E-01

3.4.1.6 Water Production Data: Data Used for Calculating Water Production for Test 2

For cages: 1,2,3,4
Desired temperature: 24+-1.5 °C Desired humidity: 30-35 percent

Day	Average RH (percent)	Room RH (percent)	Actual T (°C)	Room T (°C)	Actual[1] (g/kg)	Room[2] (g/kg)	Airflow[3] (l/min)	Dried airflow[4] (l/min)	Mice wt (g)
1	63.42	38.29	22.25	18.56	10.75	5.00	4.99	1.88	411.7
2	52.05	37.58	23.44	19.48	9.50	5.00	4.98	1.13	417.1
3	51.42	35.39	24.88	21.28	10.00	5.50	4.98	1.42	426.9
4	53.80	36.42	25.01	20.78	11.00	5.25	4.91	0.70	437.4
5	56.41	40.29	24.01	20.78	10.50	6.50	5.08	0.83	442.0
6	49.15	35.65	25.46	18.56	10.25	4.75	4.91	1.38	447.1
7	52.18	42.37	23.70	19.48	10.00	6.00	5.88	0.54	453.0
8	43.07	41.29	22.89	20.82	7.75	6.25	7.73	1.56	459.2
9	44.55	31.62	23.70	20.81	8.50	4.75	8.92	2.11	464.8
10	45.33	43.04	22.56	20.62	7.75	6.75	9.18	0.95	471.8

For cages: 5,6,7,8
Desired temperature: 24+-1.5 °C Desired humidity: 75-80 percent

Day	Average RH (percent)	Room RH (percent)	Actual T (°C)	Room T (°C)	Actual[1] (g/kg)	Room[2] (g/kg)	Airflow[3] (l/min)	Dried airflow[4] (l/min)	Mice wt (g)
1	72.82	38.29	23.03	18.56	13.25	5.00	5.02	1.51	415.9
2	80.59	37.58	22.66	19.48	14.25	5.00	5.02	0.87	415.2
3	73.85	35.39	23.63	21.28	13.75	5.50	5.11	1.07	418.1
4	80.46	36.42	24.53	20.78	15.75	5.25	4.97	1.31	427.1
5	81.55	40.29	24.02	20.78	15.24	6.50	5.02	0.48	434.2
6	73.43	35.65	24.04	18.56	14.00	4.75	5.15	0.97	444.1
7	79.63	42.37	24.60	19.48	15.50	6.00	6.07	1.52	447.2
8	75.70	41.29	22.53	20.82	13.00	6.25	7.85	0.88	453.5
9	69.52	31.62	22.58	20.81	12.00	4.75	9.24	1.54	459.9
10	76.08	43.04	23.70	20.62	14.00	6.75	8.82	2.23	463.7

For cages: 9,10,11,12
Desired temperature: 24+-1.5 °C **Desired humidity: 75-80 percent**

Day	Average RH (percent)	Room RH (percent)	Actual T (°C)	Room T (°C)	Actual[1] (g/kg)	Room[2] (g/kg)	Airflow[3] (l/min)	Dried airflow[4] (l/min)	Mice wt (g)
1	70.91	38.29	22.95	18.56	12.50	4.75	4.95	1.09	415.9
2	80.86	37.58	23.29	19.48	14.75	5.00	4.95	1.41	420.6
3	78.90	35.39	25.07	21.28	16.00	5.50	4.93	0.71	424.9
4	74.99	36.42	23.70	20.78	14.00	5.25	5.07	1.00	433.0
5	78.41	40.29	24.76	20.78	15.25	6.50	5.02	1.07	441.2
6	76.71	35.65	24.55	18.56	15.00	4.75	5.03	0.67	448.8
7	72.75	42.37	23.79	19.48	13.50	6.00	6.03	1.27	449.3
8	75.97	41.29	23.68	20.82	14.00	6.25	7.69	1.82	453.4
9	75.10	31.62	22.40	20.81	12.75	4.75	9.21	0.93	460.2
10	75.45	43.04	22.85	20.62	13.50	6.75	9.09	1.77	465.2

1. Humidity ratio (w) grams moisture per kilogram dry air for calorimeter
2. Humidity ratio (w) grams moisture per kilogram dry air for chamber
3. Total measured fresh air exchange rate
4. Portion of fresh air that pass through a column of desiccant

Water Production Data for Test 2
For cages: 1,2,3,4
Desired temperature: 24+-1.5 °C **Desired humidity: 30-35 percent**

Day	Water from air in (g/hr/100g bw)	Water from air out (g/hr/100g bw)	Water from drierite (g/hr/100g bw)	Water added (g/hr/100 bw)	Total water (g/hr/100g bw)
1	2.63E-01	9.08E-01	3.84E-01	-	1.03E+00
2	3.21E-01	7.90E-01	6.28E-01	-	1.10E+00
3	3.20E-01	8.14E-01	3.79E-01	-	8.73E-01
4	3.52E-01	8.60E-01	3.52E-01	-	8.60E-01
5	4.35E-01	8.41E-01	3.87E-01	-	7.93E-01
6	2.61E-01	7.84E-01	3.76E-01	-	8.99E-01
7	4.93E-01	9.05E-01	2.36E-01	-	6.48E-01
8	5.85E-01	9.09E-01	4.16E-01	-	7.40E-01
9	4.85E-01	1.14E+00	2.97E-01	-	9.49E-01
10	8.21E-01	1.05E+00	3.48E-01	-	5.78E-01

For cages: 5,6,7,8

Desired temperature: 24+-1.5 °C Desired humidity: 75-80 percent

Day	Water from air in (g/hr/100g bw)	Water from air out (g/hr/100g bw)	Water from drierite (g/hr/100g bw)	Water added (g/hr/100g bw)	Total water (g/hr/100g bw)
1	2.94E-01	1.11E+00	2.40E-03	0.00E+00	8.22E-01
2	3.48E-01	1.20E+00	0.00E+00	4.34E-01	4.18E-01
3	3.70E-01	1.17E+00	0.00E+00	7.18E-02	7.29E-01
4	3.14E-01	1.28E+00	8.90E-02	0.00E+00	1.05E+00
5	4.73E-01	1.23E+00	2.30E-03	0.00E+00	7.57E-01
6	3.11E-01	1.13E+00	6.76E-03	2.25E-01	6.02E-01
7	4.26E-01	1.47E+00	3.02E-01	5.81E-01	7.61E-01
8	6.69E-01	1.57E+00	8.82E-03	4.41E-02	8.64E-01
9	5.54E-01	1.68E+00	0.00E+00	3.91E-01	7.35E-01
10	6.68E-01	1.86E+00	6.47E-03	5.82E-01	6.12E-01

For cages: 9,10,11,12

Desired temperature: 24+-1.5 °C Desired humidity: 75-80 percent

Day	Water from air in (g/hr/100g bw)	Water from air out (g/hr/100g bw)	Water from drierite (g/hr/100g bw)	Water added (g/hr/100 bw)	Total water (g/hr/100g bw)
1	3.07E-01	1.04E+00	5.29E-02	0.00E+00	7.82E-01
2	2.94E-01	1.21E+00	0.00E+00	1.43E-01	7.74E-01
3	3.80E-01	1.29E+00	2.52E-01	2.35E-01	9.30E-01
4	3.44E-01	1.14E+00	1.18E-01	0.00E+00	9.16E-01
5	4.06E-01	1.21E+00	0.00E+00	0.00E+00	8.04E-01
6	3.21E-01	1.17E+00	0.00E+00	6.68E-02	7.83E-01
7	4.43E-01	1.26E+00	2.23E-03	0.00E+00	8.22E-01
8	5.64E-01	1.66E+00	0.00E+00	2.21E-01	8.71E-01
9	5.96E-01	1.78E+00	0.00E+00	8.69E-02	1.10E+00
10	7.40E-01	1.84E+00	0.00E+00	9.46E-01	1.52E-01

3.4.1.7 Raw Weight Data Test 1

Mice Weight Data

Mice weight (g)											
Day	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Cage1	99.8	101.5	103.5	105.0	107.1	107.8	108.8	110.8	110.4	113.4	115.5
Cage2	99.4	101.7	103.1	103.9	105.2	107.6	108.5	109.2	110.1	111.3	114.3
Cage3	103.3	104.2	104.9	106.5	109.4	110.4	113.2	116.3	114.8	119.1	119.7
Cage4	99.1	100.6	102.4	104.9	107.8	111.3	110.6	113.6	114.4	115.6	117.1
Total wt	**401.6**	**408.0**	**413.9**	**420.3**	**429.5**	**437.1**	**441.1**	**449.9**	**449.7**	**459.4**	**466.6**
Cage5	104.7	107.5	109.4	112.1	114.5	115.7	118.3	120.4	121.3	123.3	124.8
Cage6	100.5	100.6	103	104.4	104.8	106.6	109.4	111.3	113.4	115.7	117.7
Cage7	102.2	98.2	99.2	99.5	99.4	99.2	101.2	102.9	104.4	106.3	107.6
Cage8	102.4	103.8	105.9	108.7	109.1	111.7	113.9	114.8	115.6	115.8	116.3
Total wt	**409.8**	**410.1**	**417.5**	**424.7**	**427.8**	**433.2**	**442.8**	**449.4**	**454.7**	**461.1**	**466.4**
Cage9	104	103.5	103.7	105.6	108	108.5	110.2	110.8	112.0	112.7	114.5
Cage10	105.6	106.9	109.3	111.1	112.8	115.0	116.9	117.9	119.5	122	123.4
Cage11	105.7	106.5	107.6	109.7	112.4	114.0	114.4	114.7	117.4	117.9	119.2
Cage12	105.7	105.8	107.7	110.7	112.3	116.6	119.7	120.7	123.0	125.7	127.4
Total wt	**421**	**422.7**	**428.3**	**437.1**	**445.5**	**454.1**	**461.2**	**464.1**	**471.9**	**478.3**	**484.5**

Litter Weight

Litter weight (g)											
Day	**1**	**2**	**3**	**4**	**5**	**6**	**7***	**8***	**9***	**10**	**11**
Cage1	98.7	110.4	134.6	136.7	136.5	144.8	146.9	-44.8	169.4	179.5	180.1
Cage2	91.6	95.6	104.7	117.4	126.9	130.0	142.5	150.6	162.7	164.7	173.0
Cage3	99.7	102.2	112.0	126.6	128.2	135.8	154	167.6	183.7	189.5	192.3
Cage4	120.1	120.2	132.6	147.1	151.1	153.9	167.9	-16.4	194.2	192.7	200.9
Total litter wt	**410.1**	**428.4**	**483.9**	**527.8**	**542.7**	**564.5**	**611.3**		**710**	**726.4**	**746.3**
Cage5	93.3	110.8	132.0	160.2	157.0	174.7	192.6	20.0	226.1	226.8	239.4
Cage6	113.2	123.5	139.2	150.6	156.5	180.3	188.3	198.6	213.6	227.2	238.0
Cage7	88.1	102.4	119.0	130.2	136	140.8	149.7	159.7	176.2	185.3	187.7
Cage8	111.1	122.4	138.1	151.9	155.9	161.1	173.7	-438.8	197.7	211.5	215.0
Total litter wt	**405.7**	**459.1**	**528.3**	**592.9**	**605.4**	**656.9**	**704.3**		**813.6**	**850.8**	**880.1**
Cage9	81.2	89.2	102.0	117.6	114.0	126.7	148.4	142.8	152.4	162.5	169.5
Cage10	96.5	105.3	118.8	136.6	135.4	141.7	152.9	152.0	162.1	174.4	184.5
Cage11	106.5	110.5	119.3	129.9	142.4	151.3	-59.8	175.6	189.0	192.1	198.2
Cage12	111.3	113.4	122.4	133.5	144.9	150.7	164.9	177.8	198.4	199.4	205.1
Total litter wt	**395.5**	**418.4**	**462.5**	**517.6**	**536.7**	**570.4**		**648.2**	**701.9**	**728.4**	**757.3**

*weights were recorded wrong on day #8 which affected the data on days #7-#9

Daily Litter Weight Gain

Daily litter weight gain (g)											
Day	**1**	**2**	**3**	**4**	**5**	**6**	**7***	**8***	**9***	**10**	**Ave.**
Cage1	11.7	24.2	2.1	-0.2	8.3	2.1	-191.7	214.2	10.1	0.6	
Cage2	4.0	9.1	12.7	9.5	3.1	12.5	8.1	12.1	2.0	8.3	
Cage3	2.5	9.8	14.6	1.6	7.6	18.2	13.6	16.1	5.8	2.8	
Cage4	0.1	12.4	14.5	4.0	2.8	14.0	-184.3	210.6	-1.5	8.2	
Total litter wt gain	**18.3**	**55.5**	**43.9**	**14.9**	**21.8**	**46.8**			**16.4**	**19.9**	**29.7**
Cage5	17.5	21.2	28.2	-3.2	17.7	17.9	-172.6	206.1	0.7	12.6	
Cage6	10.3	15.7	11.4	5.9	23.8	8.0	10.3	15.0	13.6	10.8	
Cage7	14.3	16.6	11.2	5.8	4.8	8.9	10.0	16.5	9.1	2.4	
Cage8	11.3	15.7	13.8	4.0	5.2	12.6	-612.5	636.5	13.8	3.5	
Total litter wt gain	**53.4**	**69.2**	**64.6**	**12.5**	**51.5**	**47.4**			**37.2**	**29.3**	**45.6**
Cage9	8.0	12.8	15.6	-3.6	12.7	21.7	-5.6	9.6	10.1	7.0	
Cage10	8.8	13.5	17.8	-1.2	6.3	11.2	-0.9	10.1	12.3	10.1	
Cage11	4.0	8.8	10.6	12.5	8.9	-211.1	235.4	13.4	3.1	6.1	
Cage12	2.1	9.0	11.1	11.4	5.8	14.2	12.9	20.6	1.0	5.7	
Total litter wt gain	**22.9**	**44.1**	**55.1**	**19.1**	**33.7**			**53.7**	**26.5**	**28.9**	**35.5**

*weights were recorded wrong on day #8 which affected the data on days #7-#9

3.4.1.8 Raw Weight Data Test 2

Mice Weight

Mice weight (g)											
Day	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Cage1	106.6	104.6	106.4	109.4	111.8	111.7	112.5	114.0	114.4	116.4	115.6
Cage2	103.1	105.8	109.1	110.6	110.7	113.9	115.0	116.7	118.8	121.0	121.9
Cage3	103.5	105.8	108.8	110.8	112.2	113.0	115.3	116.2	117.7	118.1	118.7
Cage4	98.5	100.9	102.6	106.6	107.3	108.5	110.2	112.3	113.9	116.3	115.8
Total wt	**411.7**	**417.1**	**426.9**	**437.4**	**442.0**	**447.1**	**453.0**	**459.2**	**464.8**	**471.8**	**472.0**
Cage5	105.8	105.5	104.3	105.7	107.2	109.8	110.8	112.7	112.7	114.6	115.4
Cage6	104.1	105.4	107.1	110.2	112.7	116	116.9	119.0	121.4	120.1	119.7
Cage7	101.8	102.7	104.7	107.2	108.9	111.5	112.1	112.8	114	116.7	117.4
Cage8	104.2	101.6	102.0	104.0	105.4	106.8	107.4	109.0	111.8	112.3	112.8
Total wt	**415.9**	**415.2**	**418.1**	**427.1**	**434.2**	**444.1**	**447.2**	**453.5**	**459.9**	**463.7**	**465.3**
Cage9	103.8	102.2	103.3	105.1	107.8	109.7	110.2	110.5	111.8	112.7	115.6
Cage10	103.7	107.1	105.7	107.9	109.2	110.6	111.0	110.2	111.8	113.7	115.1
Cage11	103.2	103.5	104.3	105.1	107.4	108.9	109.0	111.5	112.3	113.8	115.2
Cage12	105.2	107.8	111.6	114.9	116.8	119.6	119.1	121.2	124.3	125.0	125.4
Total wt	**415.9**	**420.6**	**424.9**	**433.0**	**441.2**	**448.8**	**449.3**	**453.4**	**460.2**	**465.2**	**471.3**

Litter Weight

Litter weight (g)											
Day	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Cage1	70.7	82.6	93.5	105.2	122.9	125.0	131.8	140.6	153.9	160.4	177
Cage2	76.8	87.5	96.3	109.2	125.8	127.5	134.8	149.3	149.9	159.6	172.1
Cage3	89.5	99.0	109.4	120.8	136.7	141.8	153.4	165.6	176.3	180.6	192.2
Cage4	77.0	85.6	95.1	106.0	124.1	126.2	135.6	146.5	158.1	162.7	175.5
Total litter wt	**314.0**	**354.7**	**394.3**	**441.2**	**509.5**	**520.5**	**555.6**	**602.0**	**638.2**	**663.3**	**716.8**
Cage5	62.2	79.0	940	110.3	126.6	133.2	146.6	162.0	181.5	203.7	207.4
Cage6	67.9	85.0	101.6	124.6	140.3	146.8	160.2	178.2	207.8	230.4	233.2
Cage7	68.1	88.5	106.5	125.3	142.4	151.7	168.8	186.2	210.7	235.7	253.8
Cage8	70.8	88.4	110.2	127.7	146.7	158.5	172.3	188.1	208.2	219.3	225.9
Total litter wt	**269.0**	**340.9**	**412.3**	**487.9**	**556.0**	**590.2**	**647.9**	**714.5**	**808.2**	**889.1**	**920.3**
Cage9	93.6	115.6	135.8	151.2	171.1	178.2	191.6	206.3	226.2	237.6	259.9
Cage10	75.9	103.3	120.7	139.5	165.0	165.4	173.9	189.6	208.4	218.7	234.7
Cage11	65.8	88.0	105.3	123.3	142.5	154.0	168.4	183.5	204.4	217.5	233.1
Cage12	57.7	84.0	105.3	127.1	148.9	162.8	181.9	202.1	230.7	250.4	270.2
Total litter wt	**293.0**	**390.9**	**467.1**	**541.1**	**627.5**	**660.4**	**715.8**	**781.5**	**869.7**	**924.2**	**997.9**

Daily Litter Weight Gain

Daily litter weight gain (g)											
Day	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Ave.**
Cage1	11.9	10.9	11.7	17.7	2.1	6.8	8.8	13.3	6.5	16.6	
Cage2	10.7	8.8	12.9	16.6	1.7	7.3	14.5	0.6	9.7	12.5	
Cage3	9.5	10.4	11.4	15.9	5.1	11.6	12.2	10.7	4.3	11.6	
Cage4	8.6	9.5	10.9	18.1	2.1	9.4	10.9	11.6	4.6	12.8	
Total litter wt gain	**40.7**	**39.6**	**46.9**	**68.3**	**11.0**	**35.1**	**46.4**	**36.2**	**25.1**	**53.5**	**40.3**
Cage5	16.8	15.0	16.3	16.3	6.6	13.4	15.4	19.5	22.2	3.7	
Cage6	17.1	16.6	23.0	15.7	6.5	13.4	18.0	29.6	22.6	2.8	
Cage7	20.4	18.0	18.8	17.1	9.3	17.1	17.4	24.5	25.0	18.1	
Cage8	17.6	21.8	17.5	19.0	11.8	13.8	15.8	20.1	11.1	6.6	
Total litter wt gain	**71.9**	**71.4**	**75.6**	**68.1**	**34.2**	**57.7**	**66.6**	**93.7**	**80.9**	**31.2**	**65.1**
Cage9	22.0	20.2	15.4	19.9	7.1	13.4	14.7	19.9	11.4	22.3	
Cage10	27.4	17.4	18.8	25.5	0.4	8.5	15.7	18.8	10.3	16.0	
Cage11	22.2	17.3	18.0	19.2	11.5	14.4	15.1	20.9	13.1	15.6	
Cage12	26.3	21.3	21.8	21.8	13.9	19.1	20.2	28.6	19.7	19.8	
Total litter wt gain	**97.9**	**76.2**	**74.0**	**86.4**	**32.9**	**55.4**	**65.7**	**88.2**	**54.5**	**73.7**	**70.5**

3.4.1.9 Average Mass Generation Rate for All Experimental Units in Test 1

Desired temperature: 24+-1.5 °C Desired humidity: 30-35 percent

Light on			Generation rate		
Day	O_2 (l/min)	CO_2 (l/min)	CO_2 (g/hr/100g bw)	NH_3 (g/hr/100g bw)	Maximum NH_3 (g/hr/100g bw)
1	-3.57E-02	3.48E-02	9.00E-01	-9.36E-06	3.28E-05
2	-1.62E-02	2.05E-02	5.26E-01	3.13E-04	5.33E-04
3	-2.75E-02	2.34E-02	5.89E-01	4.76E-04	5.98E-04
4	-2.49E-02	2.57E-02	6.38E-01	8.48E-04	1.14E-03
5	-1.08E-02	2.03E-02	4.95E-01	1.15E-03	1.37E-03
6	-2.63E-02	2.39E-02	5.68E-01	-	-
7	-2.82E-02	2.28E-02	5.36E-01	2.40E-03	2.67E-03
8	-1.24E-02	1.69E-02	3.94E-01	1.59E-03	1.65E-03
9	-2.15E-02	2.17E-02	4.99E-01	2.75E-03	2.86E-03
10	-2.25E-02	2.27E-02	5.15E-01	3.59E-03	3.77E-03

Light off			Generation rate		
Day	O_2 (l/min)	CO_2 (l/min)	CO_2 (g/hr/100g bw)	NH_3 (g/hr/100g bw)	Maximum NH_3 (g/hr/100g bw)
1	-3.66E-02	3.98E-02	1.03E+00	5.18E-04	6.13E-04
2	-2.53E-02	2.81E-02	7.21E-01	5.34E-04	7.45E-04
3	-2.73E-02	3.26E-02	8.21E-01	7.65E-04	9.18E-04
4	-2.40E-02	3.23E-02	8.04E-01	1.25E-03	1.48E-03
5	-1.15E-02	2.87E-02	6.99E-01	6.43E-04	8.14E-04
6	-9.88E-03	3.10E-02	7.39E-01	1.47E-03	1.52E-03
7	-3.65E-02	3.72E-02	8.78E-01	2.28E-03	2.45E-03
8	-3.67E-02	3.37E-02	7.86E-01	1.95E-03	2.15E-03
9	-2.77E-02	2.75E-02	6.34E-01	4.51E-03	4.66E-03
10	-2.92E-02	3.10E-02	7.03E-01	4.53E-03	5.14E-03

Desired temperature: 24+-1.5 °C Desired humidity: 75-80 percent

Light on			Generation rate		
Day	O_2 (l/min)	CO_2 (l/min)	CO_2 (g/hr/100g bw)	NH_3 (g/hr/100g bw)	Maximum NH_3 (g/hr/100g bw)
1	-3.04E-02	2.80E-02	7.27E-01	1.78E-05	1.07E-04
2	-2.76E-02	2.69E-02	6.98E-01	3.78E-04	6.49E-04
3	-2.96E-02	2.33E-02	5.95E-01	4.95E-04	6.28E-04
4	-2.46E-02	2.41E-02	6.03E-01	2.04E-03	2.48E-03
5	-1.83E-02	2.66E-02	6.62E-01	2.34E-03	2.55E-03
6	-3.96E-02	3.30E-02	8.10E-01	-	-
7	-3.26E-02	2.25E-02	5.41E-01	3.49E-03	3.58E-03
8	-2.43E-02	2.72E-02	6.45E-01	4.26E-03	4.44E-03
9	-3.46E-02	3.08E-02	7.22E-01	3.61E-03	3.67E-03
10	-2.35E-02	2.21E-02	5.10E-01	3.46E-03	3.53E-03

Light off			Generation rate		
Day	O_2 (l/min)	CO_2 (l/min)	CO_2 (g/hr/100g bw)	NH_3 (g/hr/100g bw)	Maximum NH_3 (g/hr/100g bw)
1	-3.01E-02	2.95E-02	7.66E-01	3.88E-04	4.76E-04
2	-3.33E-02	3.07E-02	7.96E-01	5.23E-04	6.49E-04
3	-2.74E-02	3.18E-02	8.11E-01	1.46E-03	1.91E-03
4	-2.29E-02	2.83E-02	7.10E-01	3.73E-03	4.11E-03
5	-2.16E-02	3.78E-02	9.40E-01	4.06E-03	4.68E-03
6	-1.20E-02	3.87E-02	9.50E-01	4.27E-03	4.48E-03
7	-3.10E-02	2.95E-02	7.09E-01	5.22E-03	5.39E-03
8	-4.13E-02	3.77E-02	8.93E-01	7.30E-03	7.65E-03
9	-3.13E-02	3.41E-02	7.99E-01	6.60E-03	6.70E-03
10	-3.02E-02	2.65E-02	6.11E-01	5.02E-03	5.22E-03

Desired temperature: 24+-1.5 °C Desired humidity: 30-35 percent

Day	Water from air in (g/hr/100g bw)	Water from air out (g/hr/100g bw)	Water from drierite (g/hr/100g bw)	Water added (g/hr/100 bw)	Total water (g/hr/100g bw)
1	3.42E-01	9.32E-01	7.62E-01	-	1.35E+00
2	3.75E-01	8.20E-01	6.39E-01	-	1.08E+00
3	3.67E-01	6.14E-01	6.70E-01	-	9.18E-01
4	5.09E-01	7.76E-01	5.69E-01	-	8.37E-01
5	3.62E-01	7.47E-01	5.93E-01	-	9.79E-01
6	3.11E-01	6.87E-01	4.79E-01	-	8.56E-01
7	3.38E-01	7.10E-01	4.45E-01	-	8.17E-01
8	3.90E-01	6.54E-01	4.60E-01	-	7.24E-01
9	3.97E-01	7.63E-01	2.74E-01	-	6.40E-01
10	4.00E-01	6.69E-01	4.68E-01	-	7.37E-01

Desired temperature: 24+-1.5 °C Desired humidity: 75-80 percent

Day	Water from air in (g/hr/100g bw)	Water from air out (g/hr/100g bw)	Water from drierite (g/hr/100g bw)	Water added (g/hr/100g bw)	Total water (g/hr/100g bw)
1	2.98E-01	1.06E+00	1.78E-01	1.54E+00	-6.01E-01
2	2.43E-01	1.05E+00	6.22E-01	2.93E-01	1.14E+00
3	5.62E-01	1.17E+00	1.87E-01	0.00E+00	7.92E-01
4	4.25E-01	1.07E+00	1.77E-01	0.00E+00	8.20E-01
5	3.40E-01	1.24E+00	4.68E-03	3.74E-01	5.31E-01
6	3.85E-01	1.20E+00	9.70E-02	0.00E+00	9.08E-01
7	3.61E-01	1.14E+00	6.10E-02	2.60E-01	5.75E-01
8	4.61E-01	1.22E+00	4.78E-01	4.67E-01	7.75E-01
9	3.96E-01	1.06E+00	4.18E-01	2.64E-01	8.20E-01
10	3.66E-01	1.08E+00	3.73E-01	0.00E+00	1.09E+00

3.4.1.10 Average Gas Mass Generation Rate for All Experimental Units in Test 2

Desired temperature: 24+-1.5 °C Desired humidity: 30-35 percent

light on				Generation rate		
Day	O_2 (l/min)	CO_2 (l/min)	CO_2 (g/hr/100g)	Tube NH_3 (g/hr/100g)	NH_3 (g/hr/100g)	Max NH_3 (g/hr/100g)
1	-2.81E-02	2.97E-02	7.68E-01	0.00E+00	-1.84E-05	0.00E+00
2	-3.81E-02	2.79E-02	7.12E-01	0.00E+00	1.63E-04	1.63E-04
3	-2.50E-02	2.54E-02	6.32E-01	0.00E+00	8.91E-05	1.07E-04
4	-2.95E-02	2.43E-02	5.90E-01	5.13E-05	1.03E-04	1.03E-04
5	-3.57E-02	-	-	5.24E-05	5.07E-04	5.76E-04
6	-2.45E-02	2.23E-02	5.32E-01	2.00E-04	7.65E-04	8.98E-04
7	-3.74E-02	2.59E-02	6.08E-01	1.19E-04	5.97E-04	5.97E-04
8	-2.85E-02	2.06E-02	4.76E-01	1.53E-04	1.58E-03	2.14E-03
9	-2.71E-02	1.84E-02	4.21E-01	7.54E-04	8.28E-04	8.87E-04
10	-2.45E-02	2.11E-02	4.76E-01	1.02E-03	1.83E-03	2.66E-03

Light off				Generation rate		
Day	O_2 (l/min)	CO_2 (l/min)	CO_2 (g/hr/100g)	Tube NH_3 (g/hr/100g)	NH_3 (g/hr/100g)	Max NH_3 (g/hr/100g)
1	-3.99E-02	3.45E-02	8.90E-01	0.00E+00	9.21E-05	1.11E-04
2	-3.31E-02	3.51E-02	8.96E-01	0.00E+00	0.00E+00	0.00E+00
3	-3.80E-02	3.54E-02	8.81E-01	0.00E+00	5.30E-05	1.06E-04
4	-3.77E-02	3.60E-02	8.77E-01	5.10E-05	2.89E-04	3.06E-04
5	-4.57E-02	2.96E-02	7.13E-01	7.86E-05	5.94E-04	6.29E-04
6	-3.44E-02	3.05E-02	7.26E-01	2.51E-04	1.05E-03	1.10E-03
7	-3.30E-02	3.92E-02	9.21E-01	1.17E-04	1.02E-03	1.41E-03
8	-3.38E-02	3.43E-02	7.95E-01	3.84E-04	-	-
9	-3.81E-02	2.99E-02	6.84E-01	9.49E-04	3.68E-03	4.66E-03
10	-2.75E-02	3.06E-02	6.90E-01	1.06E-03	2.75E-03	3.82E-03

Desired temperature: 24+-1.5 °C Desired humidity: 75-80 percent

Light on				Generation rate		
Day	O_2 (l/min)	CO_2 (l/min)	CO_2 (g/hr/100g)	Tube NH_3 (g/hr/100g)	NH_3 (g/hr/100g)	Max NH_3 (g/hr/100g)
1	-3.84E-02	3.14E-02	8.03E-01	2.76E-05	1.84E-05	2.76E-05
2	-4.17E-02	2.90E-02	7.37E-01	0.00E+00	1.82E-04	1.91E-04
3	-3.49E-02	2.91E-02	7.35E-01	0.00E+00	1.01E-04	1.38E-04
4	-3.65E-02	2.71E-02	6.70E-01	2.55E-04	1.16E-04	1.34E-04
5	-4.36E-02	-	-	2.05E-03	1.50E-03	1.73E-03
6	-3.18E-02	2.17E-02	5.18E-01	4.53E-03	4.80E-03	4.99E-03
7	-3.93E-02	2.67E-02	6.32E-01	5.28E-03	5.50E-03	5.62E-03
8	-4.34E-02	2.42E-02	5.68E-01	8.29E-03	1.01E-02	1.03E-02
9	-4.93E-02	2.65E-02	6.12E-01	1.11E-02	1.17E-02	1.30E-02
10	-4.12E-02	3.27E-02	7.48E-01	9.88E-03	9.84E-03	1.08E-02

Light off				Generation rate		
Day	O_2 (l/min)	CO_2 (l/min)	CO_2 (g/hr/100g)	Tube NH_3 (g/hr/100g)	NH_3 (g/hr/100g)	Max NH_3 (g/hr/100g)
1	-4.29E-02	3.35E-02	8.57E-01	0.00E+00	1.27E-04	1.63E-04
2	-4.47E-02	3.52E-02	8.97E-01	0.00E+00	3.61E-05	5.41E-05
3	-3.97E-02	3.78E-02	9.55E-01	0.00E+00	8.09E-05	1.08E-04
4	-4.18E-02	3.60E-02	8.89E-01	4.76E-04	4.50E-04	5.29E-04
5	-4.75E-02	3.28E-02	7.99E-01	3.16E-03	2.75E-03	2.88E-03
6	-3.40E-02	3.41E-02	8.12E-01	5.08E-03	6.56E-03	6.97E-03
7	-4.19E-02	4.12E-02	9.78E-01	6.54E-03	8.58E-03	9.13E-03
8	-4.83E-02	3.71E-02	8.71E-01	9.86E-03	1.07E-02	1.11E-02
9	-5.22E-02	3.56E-02	8.23E-01	1.23E-02	1.28E-02	1.34E-02
10	-4.64E-02	3.46E-02	7.92E-01	1.08E-02	1.09E-02	1.17E-02

Desired temperature: 24+-1.5 °C Desired humidity: 30-35 percent

Day	Water from air in (g/hr/100g bw)	Water from air out (g/hr/100g bw)	Water from drierite (g/hr/100g bw)	Water added (g/hr/100 bw)	Total water (g/hr/100g bw)
1	2.63E-01	9.08E-01	3.84E-01	-	1.03E+00
2	3.21E-01	7.90E-01	6.28E-01	-	1.10E+00
3	3.20E-01	8.14E-01	3.79E-01	-	8.73E-01
4	3.52E-01	8.60E-01	3.52E-01	-	8.60E-01
5	4.35E-01	8.41E-01	3.87E-01	-	7.93E-01
6	2.61E-01	7.84E-01	3.76E-01	-	8.99E-01
7	4.93E-01	9.05E-01	2.36E-01	-	6.48E-01
8	5.85E-01	9.09E-01	4.16E-01	-	7.40E-01
9	4.85E-01	1.14E+00	2.97E-01	-	9.49E-01
10	8.21E-01	1.05E+00	3.48E-01	-	5.78E-01

Desired temperature: 24+-1.5 °C Desired humidity: 75-80 percent

Day	Water from air in (g/hr/100g bw)	Water from air out (g/hr/100g bw)	Water from drierite (g/hr/100g bw)	Water added (g/hr/100g bw)	Total water (g/hr/100g bw)
1	3.01E-01	1.08E+00	2.77E-02	0.00E+00	8.02E-01
2	3.21E-01	1.20E+00	0.00E+00	2.88E-01	5.96E-01
3	3.75E-01	1.23E+00	1.26E-01	1.54E-01	8.29E-01
4	3.29E-01	1.21E+00	1.03E-01	0.00E+00	9.84E-01
5	4.39E-01	1.22E+00	1.15E-03	0.00E+00	7.80E-01
6	3.16E-01	1.15E+00	3.38E-03	1.46E-01	6.92E-01
7	4.34E-01	1.36E+00	1.52E-01	2.91E-01	7.91E-01
8	6.16E-01	1.61E+00	4.41E-03	1.32E-01	8.68E-01
9	5.75E-01	1.73E+00	0.00E+00	2.39E-01	9.15E-01
10	7.04E-01	1.85E+00	3.23E-03	7.64E-01	3.82E-01

3.4.1.11 Averaged Data for All Experimental Units From Both Test 1 and Test 2: NH_3 Generation Rate

Light on								
Day	**30-35 percent for test 1 NH_3 (g/hr/100g)**	**30 –35 percent for test 2 NH_3 (g/hr/100g)**	**Average 30 –35 percent generation rate[1] NH_3 (g/hr/100g)**	**75 –80 percent for test 1 NH_3 (g/hr/100g)**	**75 –80 percent for test 2 NH_3 (g/hr/100g)**	**Average75 –80 percent generation rate[1] NH_3 (g/hr/100g)**	**30 –35 percent generation rate[2] Tube NH_3 (g/hr/100g)**	**75 –80 percent generation rate[2] Tube NH_3 (g/hr/100g)**
1	-9.36E-06	-1.84E-05	-1.39E-05	1.78E-05	1.84E-05	1.81E-05	0.00E+00	2.76E-05
2	3.13E-04	1.63E-04	2.38E-04	3.78E-04	1.82E-04	2.80E-04	0.00E+00	0.00E+00
3	4.76E-04	8.91E-05	2.83E-04	4.95E-04	1.01E-04	2.98E-04	0.00E+00	0.00E+00
4	8.48E-04	1.03E-04	4.75E-04	2.04E-03	1.16E-04	1.08E-03	5.13E-05	2.55E-04
5	1.15E-03	5.07E-04	8.29E-04	2.34E-03	1.50E-03	1.92E-03	5.24E-05	2.05E-03
6	-	7.65E-04	7.65E-04	-	4.80E-03	4.80E-03	2.00E-04	4.53E-03
7	2.40E-03	5.97E-04	1.50E-03	3.49E-03	5.50E-03	4.50E-03	1.19E-04	5.28E-03
8	1.59E-03	1.58E-03	1.59E-03	4.26E-03	1.01E-02	7.18E-03	1.53E-04	8.29E-03
9	2.75E-03	8.28E-04	1.79E-03	3.61E-03	1.17E-02	7.66E-03	7.54E-04	1.11E-02
10	3.59E-03	1.83E-03	2.71E-03	3.46E-03	9.84E-03	6.65E-03	1.02E-03	9.88E-03

Light off								
Day	**30 –35 percent for test 1 NH_3 (g/hr/100g)**	**30-35 percent for test 2 NH_3 (g/hr/100g)**	**Average 30-35 percent generation rate[1] NH_3 (g/hr/100g)**	**75-80 percent for test 1 NH_3 (g/hr/100g)**	**75-80 percent for test 2 NH_3 (g/hr/100g)**	**Average 75-80 percent generation rate[1] NH_3 (g/hr/100g)**	**30-35 percent generation rate[2] Tube NH_3 (g/hr/100g)**	**75-80 percent generation rate[2] Tube NH_3 (g/hr/100g)**
1	5.18E-04	9.21E-05	3.05E-04	3.88E-04	1.27E-04	2.57E-04	0.00E+00	0.00E+00
2	5.34E-04	0.00E+00	2.67E-04	5.23E-04	3.61E-05	2.79E-04	0.00E+00	0.00E+00
3	7.65E-04	5.30E-05	4.09E-04	1.46E-03	8.09E-05	7.69E-04	0.00E+00	0.00E+00
4	1.25E-03	2.89E-04	7.68E-04	3.73E-03	4.50E-04	2.09E-03	5.10E-05	4.76E-04
5	6.43E-04	5.94E-04	6.18E-04	4.06E-03	2.75E-03	3.41E-03	7.86E-05	3.16E-03
6	1.47E-03	1.05E-03	1.26E-03	4.27E-03	6.56E-03	5.42E-03	2.51E-04	5.08E-03
7	2.28E-03	1.02E-03	1.65E-03	5.22E-03	8.58E-03	6.90E-03	1.17E-04	6.54E-03
8	1.95E-03	-	1.95E-03	7.30E-03	1.07E-02	9.00E-03	3.84E-04	9.86E-03
9	4.51E-03	3.68E-03	4.10E-03	6.60E-03	1.28E-02	9.71E-03	9.49E-04	1.23E-02
10	4.53E-03	2.75E-03	3.64E-03	5.02E-03	1.09E-02	7.98E-03	1.06E-03	1.08E-02

1. Data from PhD gas detector | 2. Data from colormetric tubes

3.4.1.12 Averaged Data for All Experimental Units From Both Test 1 and Test 2: Water Production

Day	30-35 percent for test 1 Total water (g/hr/100g)	30-35 percent for test 2 Total water (g/hr/100g)	Average 30-35 percent Total water (g/hr/100g)	75-80 percent for test 1 Total water (g/hr/100g)	75-80 percent for test 2 Total water (g/hr/100g)	Average75-80 percent Total water (g/hr/100g)
1	1.35E+00	1.03E+00	1.19E+00	-6.01E-01*	8.02E-01	8.02E-01
2	1.08E+00	1.10E+00	1.09E+00	1.14E+00	5.96E-01	8.68E-01
3	9.18E-01	8.73E-01	8.95E-01	7.92E-01	8.29E-01	8.11E-01
4	8.37E-01	8.60E-01	8.48E-01	8.20E-01	9.84E-01	9.02E-01
5	9.79E-01	7.93E-01	8.86E-01	5.31E-01	7.80E-01	6.56E-01
6	8.56E-01	8.99E-01	8.77E-01	9.08E-01	6.92E-01	8.00E-01
7	8.17E-01	6.48E-01	7.32E-01	5.75E-01	7.91E-01	6.83E-01
8	7.24E-01	7.40E-01	7.32E-01	7.75E-01	8.68E-01	8.21E-01
9	6.40E-01	9.49E-01	7.94E-01	8.20E-01	9.15E-01	8.67E-01
10	7.37E-01	5.78E-01	6.58E-01	1.09E+00	3.82E-01	7.36E-01
Average =	**8.94E-01**	**8.46E-01**	**8.70E-01**	**8.28E-01**	**7.64E-01**	**7.95E-01**

*Erroneous value: not included in Average Values.

3.4.1.13 Miscellaneous

Feed Weight Test 1

	Feed weight (g)										
Day	**1**	**2**	**3**	**4**	**5**	**6**	**7***	**8***	**9***	**10**	**11**
Cage1 Feed	190.5	163.0	144.2	125.0	104.0	84.2	217.2	196.7	178.5	160.2	141.4
Cage2 Feed	205.6	184.3	161.6	142.6	121.8	101.9	215.1	194.9	176.2	158.3	138.4
Cage3 Feed	183.6	159.4	139.8	120.3	99.0	79.7	232.9	210.8	191.3	170.8	150.9
Cage4 Feed	189.3	165.8	143.8	125.0	103.7	82.0	194.3	171.8	152.8	133.9	114.3
Total feed wt	**769.0**	**672.5**	**589.4**	**512.9**	**428.5**	**347.8**	**859.5**	**774.2**	**698.8**	**623.2**	**545**
Cage5 Feed	196.5	176.4	155.6	128.9	104.3	83.9	203.9	181.2	158.0	135.0	111.7
Cage6 Feed	188.9	171	147.1	123.2	101.2	81.2	173.8	151.8	126.9	103.4	81.0
Cage7 Feed	197.5	182.1	164.1	142.6	124.0	111.0	221.9	202.4	181.0	162.6	141.2
Cage8 Feed	193.3	174.7	153.3	128.1	106.1	86.5	194.4	-402.8	150.6	129.0	108.7
Total feed wt	**776.2**	**704.2**	**620.1**	**522.8**	**435.6**	**362.6**	**794.0**		**616.5**	**530.0**	**442.6**
Cage9 Feed	193.5	168.8	147.7	126.7	103.6	84.0	197.4	176.6	154.2	134.3	114.7
Cage10 Feed	192.1	166.6	143.9	121.7	100.3	78.7	207.5	187.3	165.5	144.8	124.2
Cage11 Feed	193.0	166.3	143.7	121.5	97.9	74.6	182.2	160.2	138.3	118.8	98.5
Cgae12 Feed	181.2	157.7	137.7	115.4	94.9	71.7	167.7	146.1	124.6	104.4	83.7
Total feed wt	**759.8**	**659.4**	**573.0**	**485.3**	**396.7**	**309.0**	**754.8**	**670.2**	**582.6**	**502.3**	**421.1**

*weights were recorded wrong on day #8 which affected the data on days #7-#9

Feed Weight Test 2

Feed weight (g)											
Day	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Cage1 Feed	180.0	155.0	132.2	110.1	87.7	176.1	155.0	134.8	114.3	94.1	75.5
Cage2 Feed	221.8	195.5	173.3	151.3	132.2	206.1	184.7	164.3	144.4	122.5	102.8
Cage3 Feed	243.4	218.5	194.3	168.8	146.6	227.4	203.4	181.2	158.7	139.3	118.7
Cage4 Feed	220.5	196.8	175.1	152.2	130.8	196.5	175.0	153.6	132.3	110.7	91.0
Total feed wt	**865.7**	**765.8**	**674.9**	**582.4**	**497.3**	**806.1**	**718.1**	**633.9**	**549.7**	**466.6**	**388**
Cage5 Feed	255.7	236.3	217.3	194.4	170.2	223.7	202.3	179.4	158.8	133.7	112.2
Cage6 Feed	301.1	281.4	258.9	231.9	206.3	177.7	155.1	129.9	105.3	82.3	60.3
Cage7 Feed	243.7	222.6	197.4	171.1	144.3	212.6	187.3	163.8	137.0	101.5	70.7
Cage8 Feed	299.2	282.2	258.2	230.9	202.6	251.1	227.1	203.1	179.2	155.6	135.2
Total feed wt	**1099.7**	**1022.5**	**931.8**	**828.3**	**723.4**	**865.1**	**771.8**	**676.2**	**580.3**	**473.1**	**378.4**
Cage9 Feed	286.6	266.7	243.3	218.8	193.6	264.4	241.8	219.2	197.4	172.3	145.8
Cage10 Feed	279.1	254.0	231.5	207.3	181.0	232.7	213.5	190.9	169.9	145.4	121.8
Cage11 Feed	241.4	219.0	195.9	170.3	145.4	222.7	204.5	182.4	160.8	136.7	113.5
Cgae12 Feed	261.4	235.4	207.0	176.7	147.4	253.5	227.3	197.2	162.8	132.1	105.2
Total feed wt	**1068.5**	**975.1**	**877.7**	**773.1**	**667.4**	**973.3**	**887.1**	**789.7**	**690.9**	**586.5**	**486.3**

Daily Feed Disappearance Test 1

Daily feed disappearance (g)											
Day	**1**	**2**	**3**	**4**	**5**	**6**	**7***	**8***	**9***	**10**	**Ave.**
Cage1	27.5	18.8	19.2	21.0	19.8	21.9	20.5	18.2	18.3	18.8	
Cage2	21.3	22.7	19.0	20.8	19.9	24.4	20.2	18.7	17.9	19.9	
Cage3	24.2	19.6	19.5	21.3	19.3	24.3	22.1	19.5	20.5	19.9	
Cage4	23.5	220	18.8	21.3	21.7	23.6	22.5	19.0	18.9	19.6	
TAFD	**96.5**	**83.1**	**76.5**	**84.4**	**80.7**	**94.2**	**85.3**	**75.4**	**75.6**	**78.2**	**83.0**
Cage5	20.1	20.8	26.7	24.6	20.4	23.2	22.7	23.2	23.0	23.3	
Cage6	17.9	23.9	23.9	22.0	20.0	22.3	22.0	24.9	23.5	22.4	
Cage7	15.4	18.0	21.5	18.6	13.0	17.6	19.5	21.4	18.4	21.4	
Cage8	18.6	21.4	25.2	22.0	19.6	21.2	597.2	-553.4	21.6	20.3	
TAFD	**72.0**	**84.1**	**97.3**	**87.2**	**73.0**	**84.3**			**86.5**	**87.4**	**84.0**
Cage9	24.7	21.1	21.0	23.1	19.6	25.3	20.8	22.4	19.9	19.6	
Cage10	25.5	22.7	22.2	21.4	21.6	25.3	20.2	21.8	20.7	20.6	
Cage11	26.7	22.6	22.2	23.6	23.3	24.2	22.0	21.9	19.5	20.3	
Cage12	23.5	20.0	22.3	20.5	23.2	26.3	21.6	21.5	20.2	20.7	
TAFD	**100.4**	**86.4**	**87.7**	**88.6**	**87.7**	**101.1**	**84.6**	**87.6**	**80.3**	**81.2**	**88.6**

*weights were recorded wrong on day #8 which affected the data on days #7-#9

TFD Total Feed Disappearance

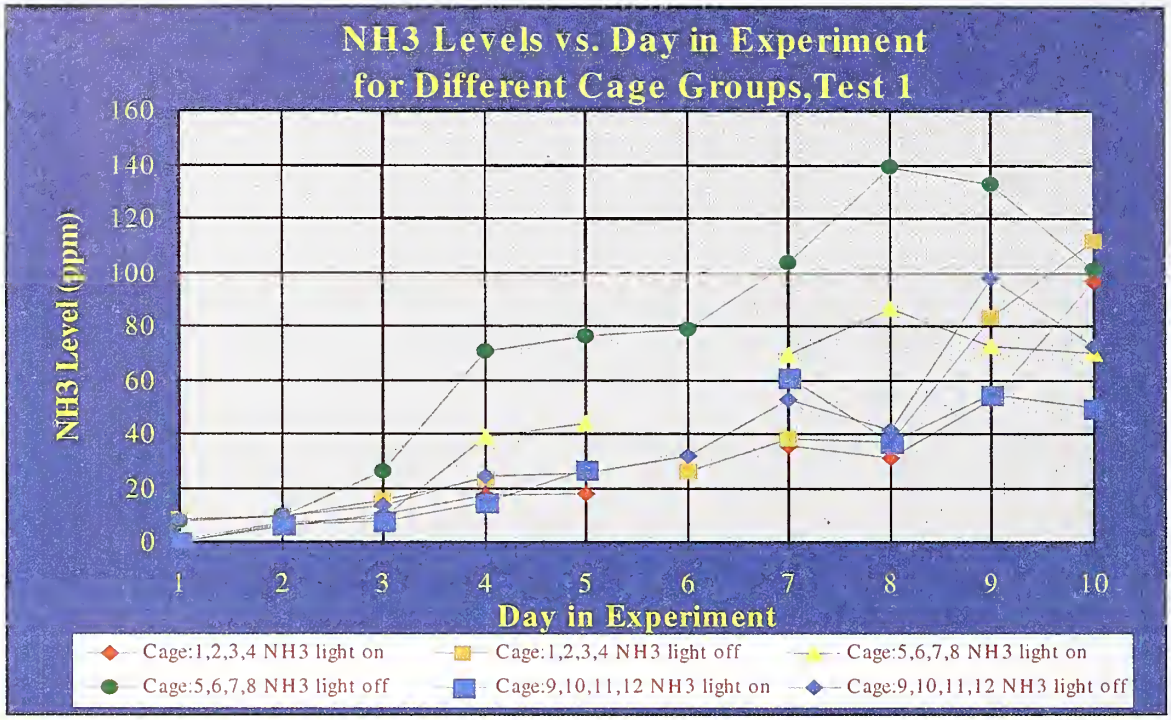
Daily Feed Disappearance Test 2

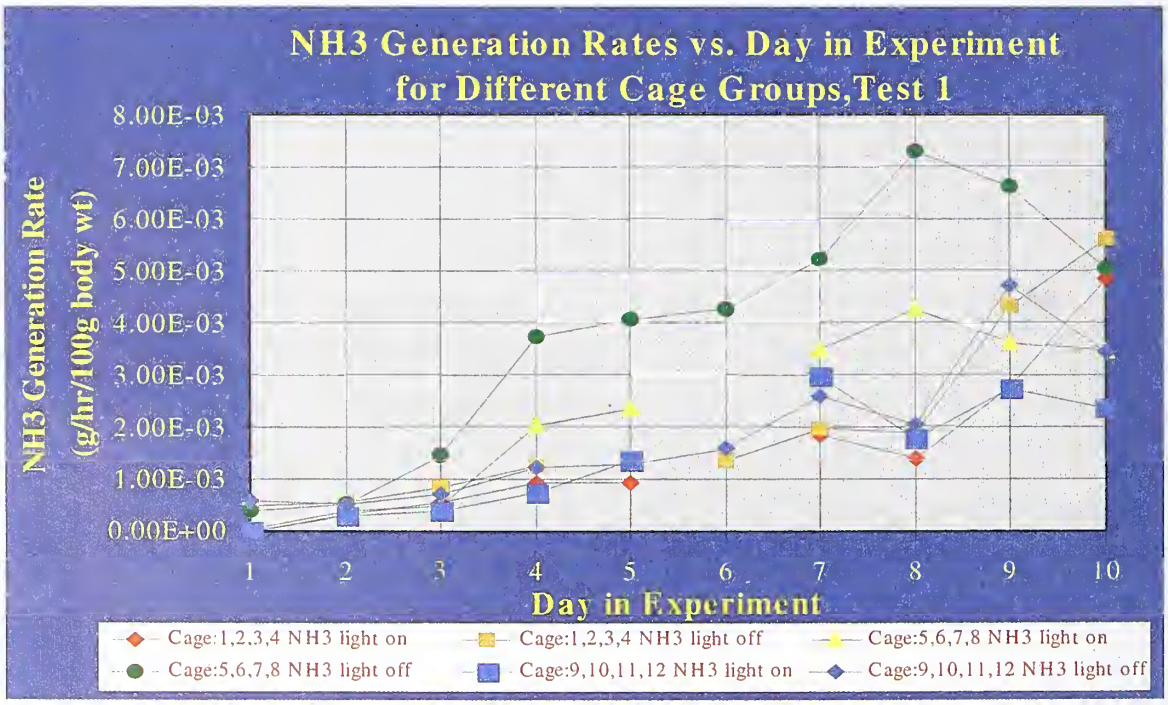
Daily feed disappearance (g)											
Day	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Average**
Cage1	25.0	22.8	22.1	22.4	27.4	21.1	20.2	20.5	20.2	18.6	
Cage2	26.3	22.2	22.0	19.1	24.7	21.4	20.4	19.9	21.9	19.7	
Cage3	24.9	24.2	25.5	22.2	27.4	24.0	22.2	22.5	19.4	20.6	
Cage4	23.7	21.7	22.9	21.4	24.4	21.5	21.4	21.3	21.6	19.7	
TAFD	**99.9**	**90.9**	**92.5**	**85.1**	**103.9**	**88.0**	**84.2**	**84.2**	**83.1**	**78.6**	**89.0**
Cage5	19.4	19.0	22.9	24.2	23.8	21.4	22.9	20.6	25.1	21.5	
Cage6	19.7	22.5	27.0	25.6	28.6	22.6	25.2	24.6	23.0	22.0	
Cage7	21.1	25.2	26.3	26.8	27.0	25.3	23.5	26.8	35.5	30.8	
Cage8	17.0	24.0	27.3	28.3	28.1	24.0	24.0	23.9	23.6	20.4	
TAFD	**77.2**	**90.7**	**103.5**	**104.9**	**107.5**	**93.3**	**95.6**	**95.9**	**107.2**	**94.7**	**97.1**
Cage9	19.9	23.4	24.5	25.2	25.9	22.6	22.6	21.8	25.1	26.5	
Cage10	25.1	22.5	24.2	26.3	25.7	19.2	22.6	21.0	24.5	23.6	
Cage11	22.4	23.1	25.6	24.9	25.5	18.2	22.1	21.6	24.1	23.2	
Cage12	26.0	28.4	30.3	29.3	28.6	26.2	30.1	34.4	30.7	26.9	
TAFD	**93.4**	**97.4**	**104.6**	**105.7**	**105.7**	**86.2**	**97.4**	**98.8**	**104.4**	**100.2**	**99.4**

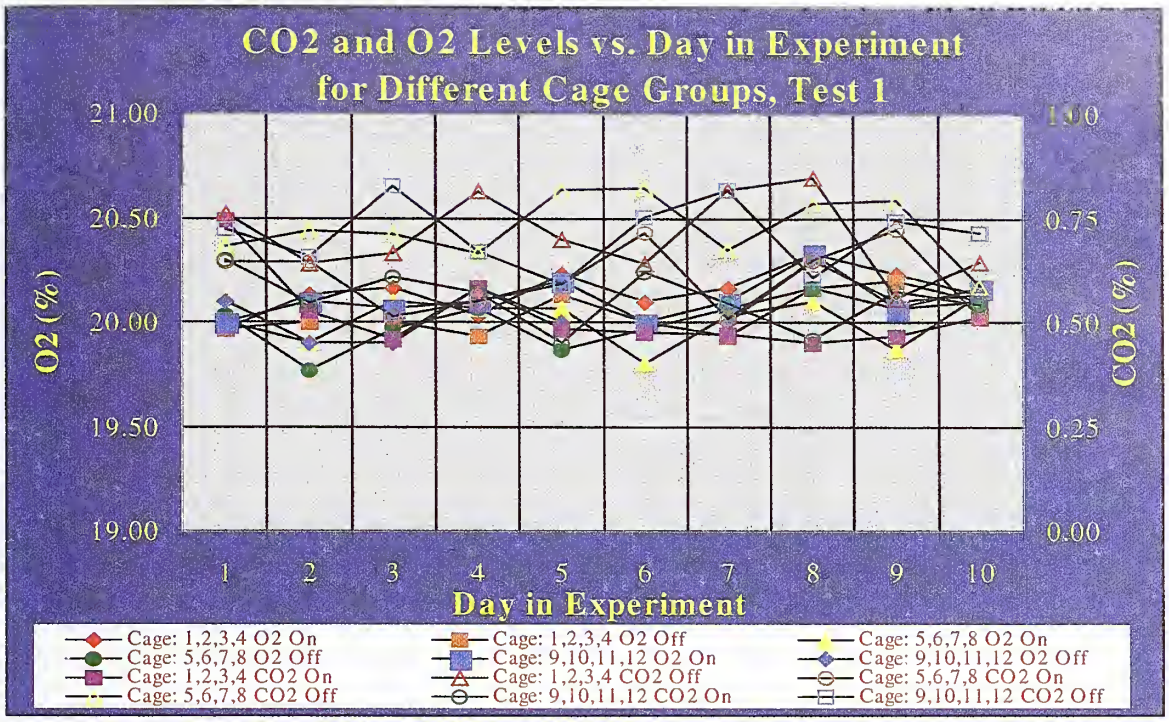
TFD Total Feed Disappearance

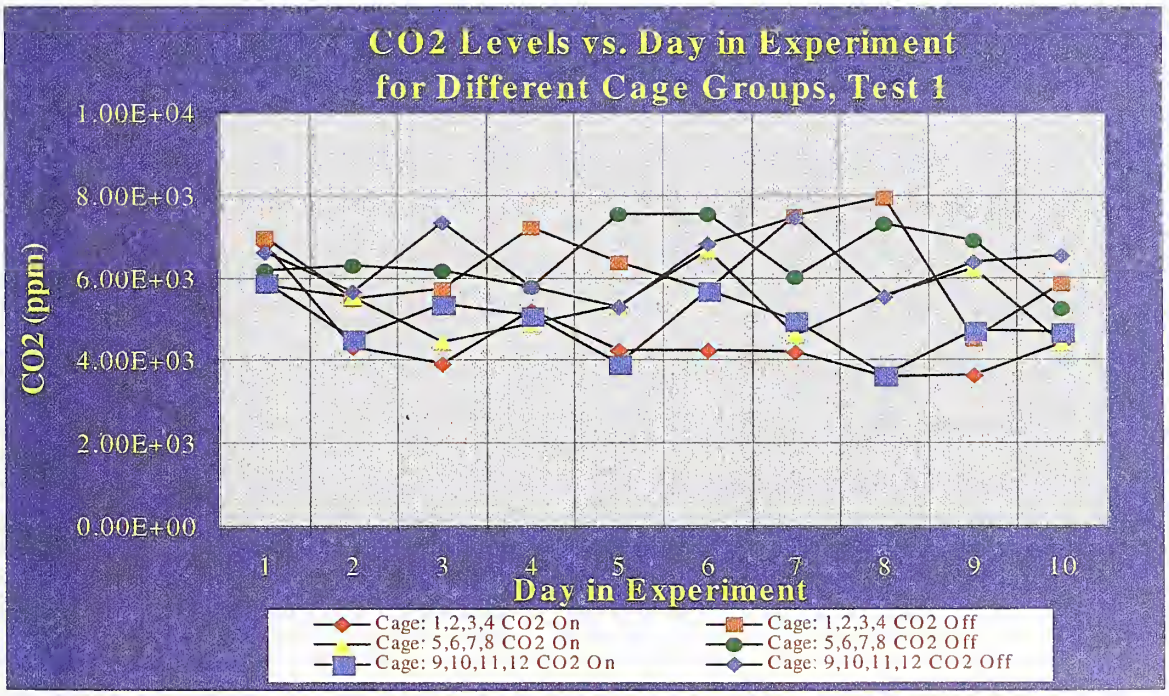
3.4.2 Graphical Representation of Data

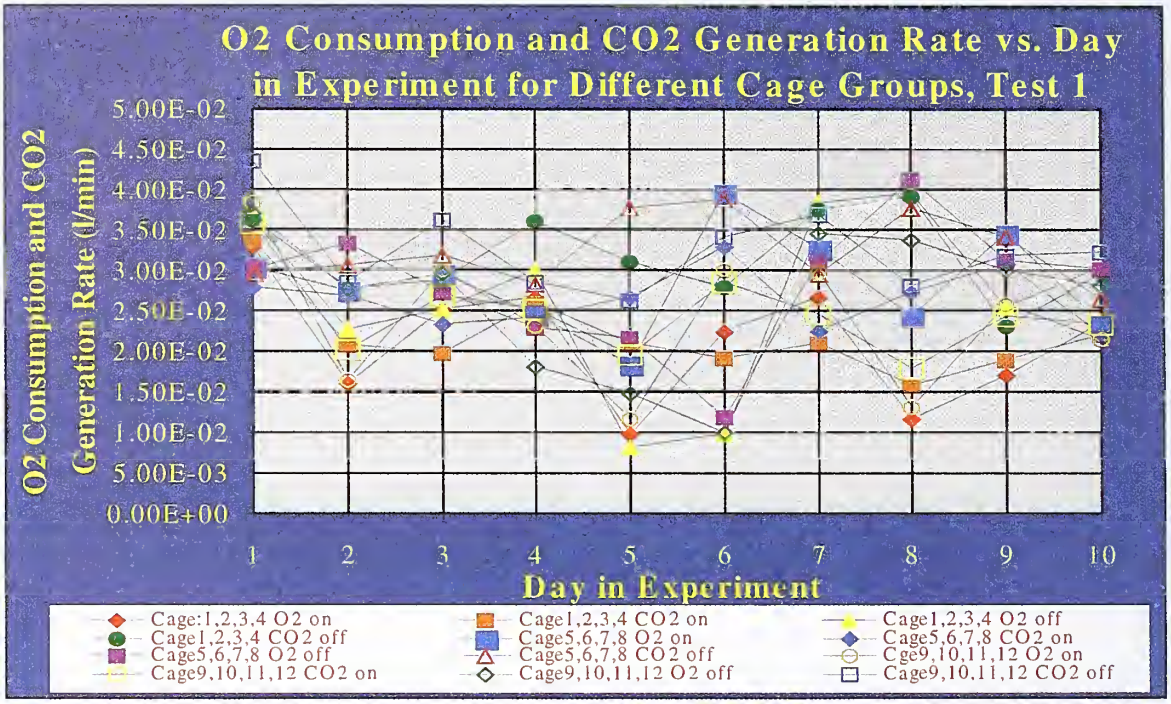
3.4.2.1 Gas Concentration and Mass Generation Rates: Individual Calorimeter Data (O_2, CO_2, and NH_3) for Test 1

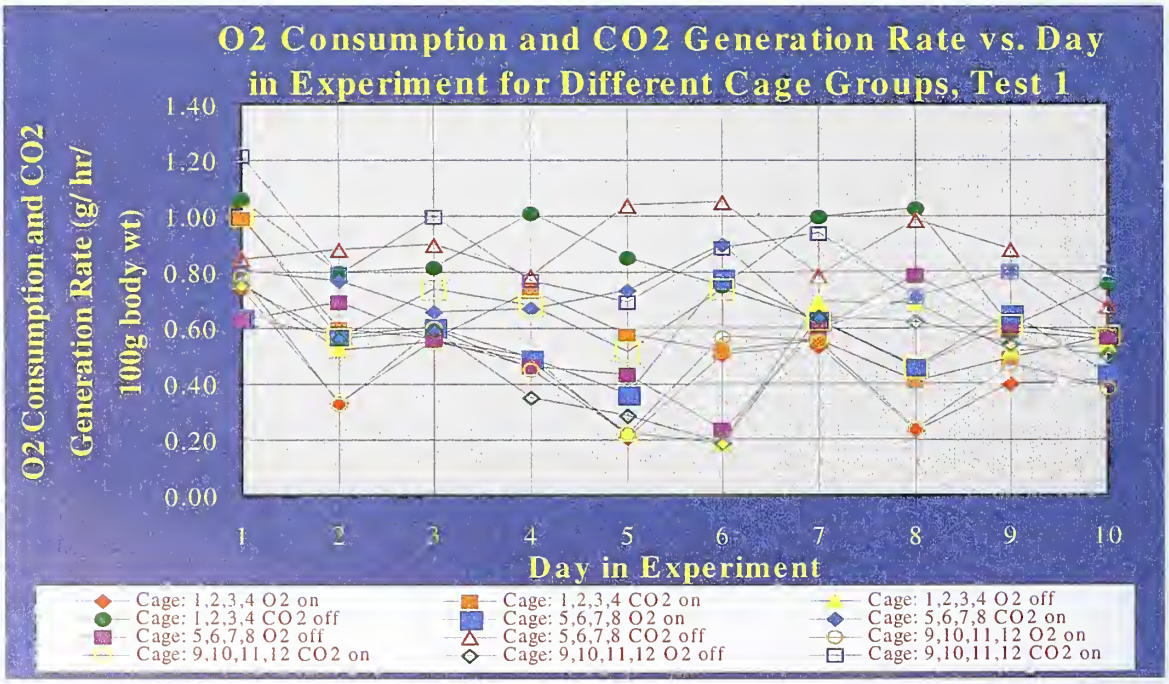


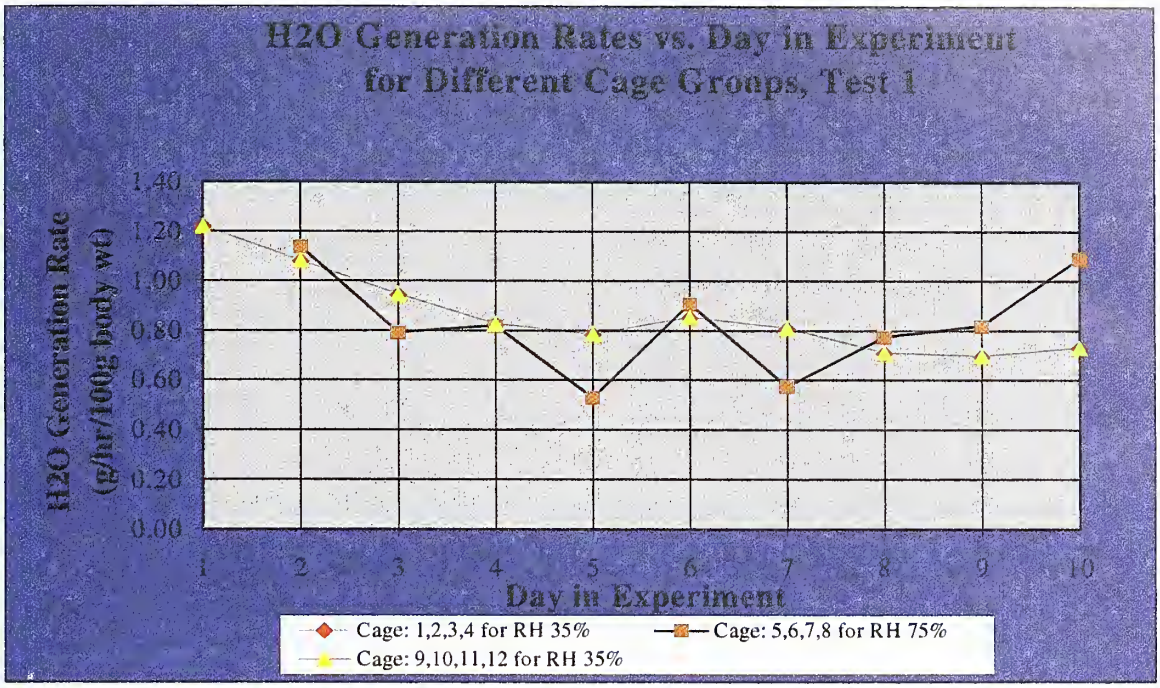



CO2 and O2 Levels vs. Day in Experiment
for Different Cage Groups, Test 1
O2 (%)
21.00
20.50
20.00
19.50
19.00
CO2 (%)
1.00
0.75
0.50
0.25
0.00
1 2 3 4 5 6 7 8 9 10
Day in Experiment
Cage: 1,2,3,4 O2 On
Cage: 1,2,3,4 O2 Off
Cage: 5,6,7,8 O2 On
Cage: 5,6,7,8 O2 Off
Cage: 9,10,11,12 O2 On
Cage: 9,10,11,12 O2 Off
Cage: 1,2,3,4 CO2 On
Cage: 1,2,3,4 CO2 Off
Cage: 5,6,7,8 CO2 On
Cage: 5,6,7,8 CO2 Off
Cage: 9,10,11,12 CO2 On
Cage: 9,10,11,12 CO2 Off

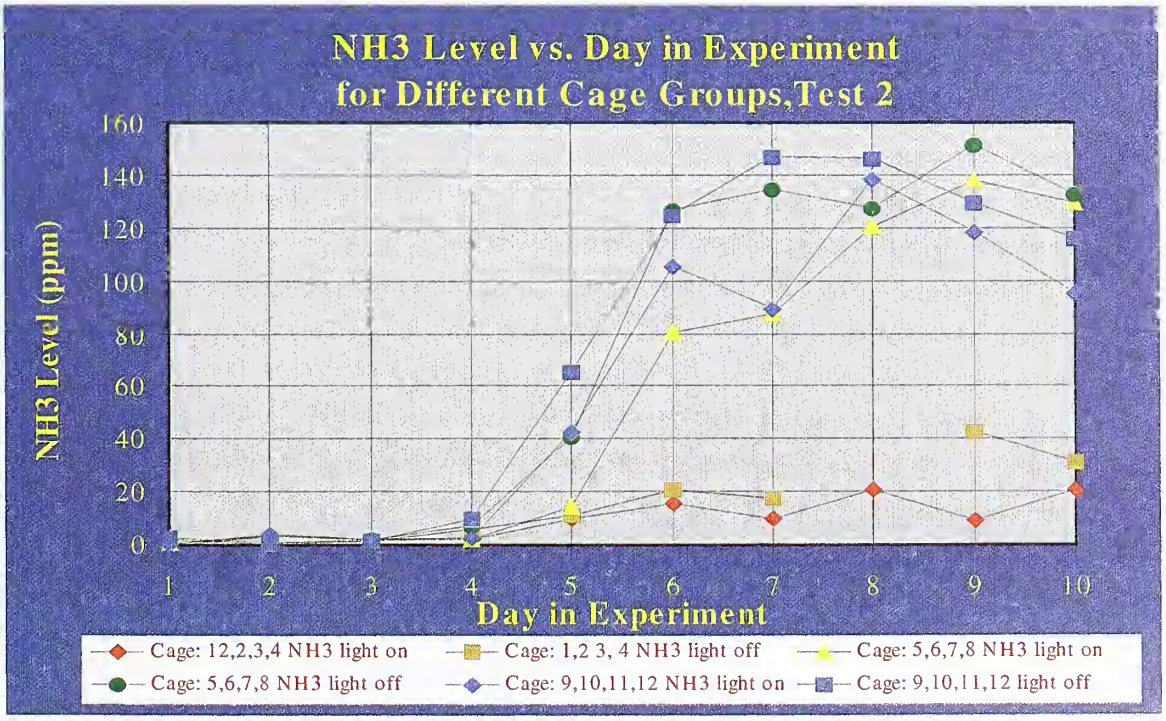

CO2 Levels vs. Day in Experiment
for Different Cage Groups, Test 1
CO2 (ppm)
1.00E+04
8.00E+03
6.00E+03
4.00E+03
2.00E+03
0.00E+00
1 2 3 4 5 6 7 8 9 10
Day in Experiment
Cage: 1,2,3,4 CO2 On
Cage: 1,2,3,4 CO2 Off
Cage: 5,6,7,8 CO2 On
Cage: 5,6,7,8 CO2 Off
Cage: 9,10,11,12 CO2 On
Cage: 9,10,11,12 CO2 Off

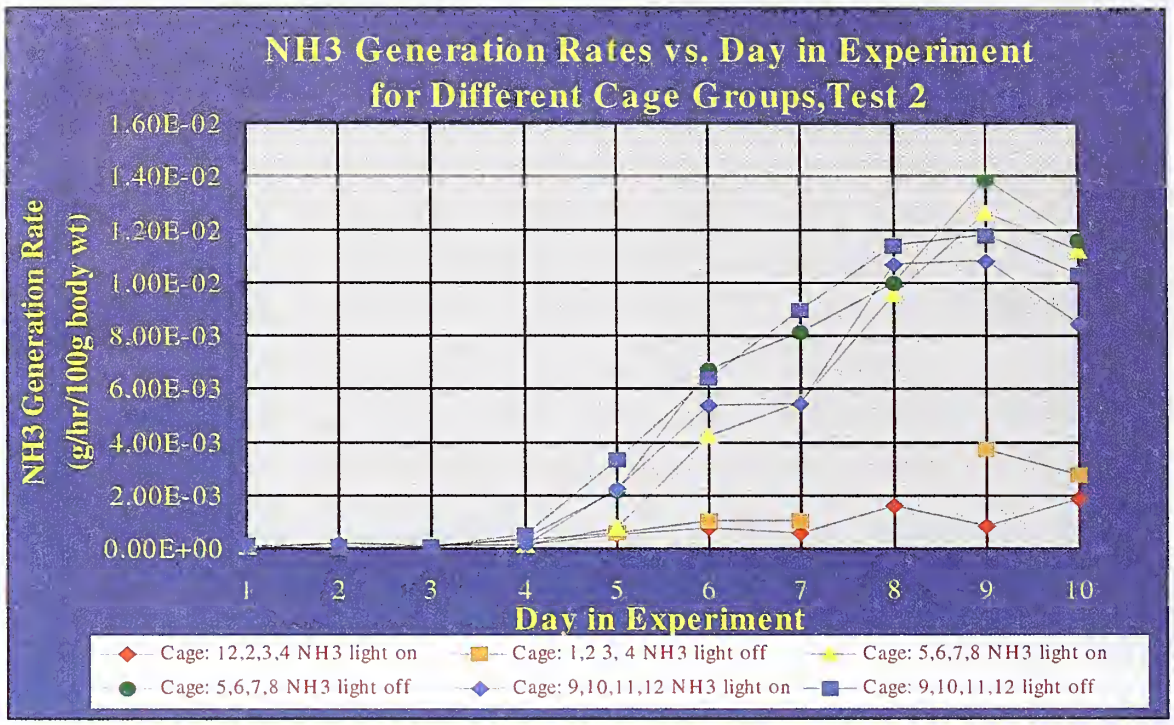

O2 Consumption and CO2 Generation Rate vs. Day in Experiment for Different Cage Groups, Test 1
O2 Consumption and CO2 Generation Rate (l/min)
5.00E-02
4.50E-02
4.00E-02
3.50E-02
3.00E-02
2.50E-02
2.00E-02
1.50E-02
1.00E-02
5.00E-03
0.00E+00
1 2 3 4 5 6 7 8 9 10
Day in Experiment
Cage:1,2,3,4 O2 on
Cage1,2,3,4 CO2 on
Cage1,2,3,4 O2 off
Cage1,2,3,4 CO2 off
Cage5,6,7,8 O2 on
Cage5,6,7,8 CO2 on
Cage5,6,7,8 O2 off
Cage5,6,7,8 CO2 off
Cge9,10,11,12 O2 on
Cage9,10,11,12 CO2 on
Cage9,10,11,12 O2 off
Cage9,10,11,12 CO2 off

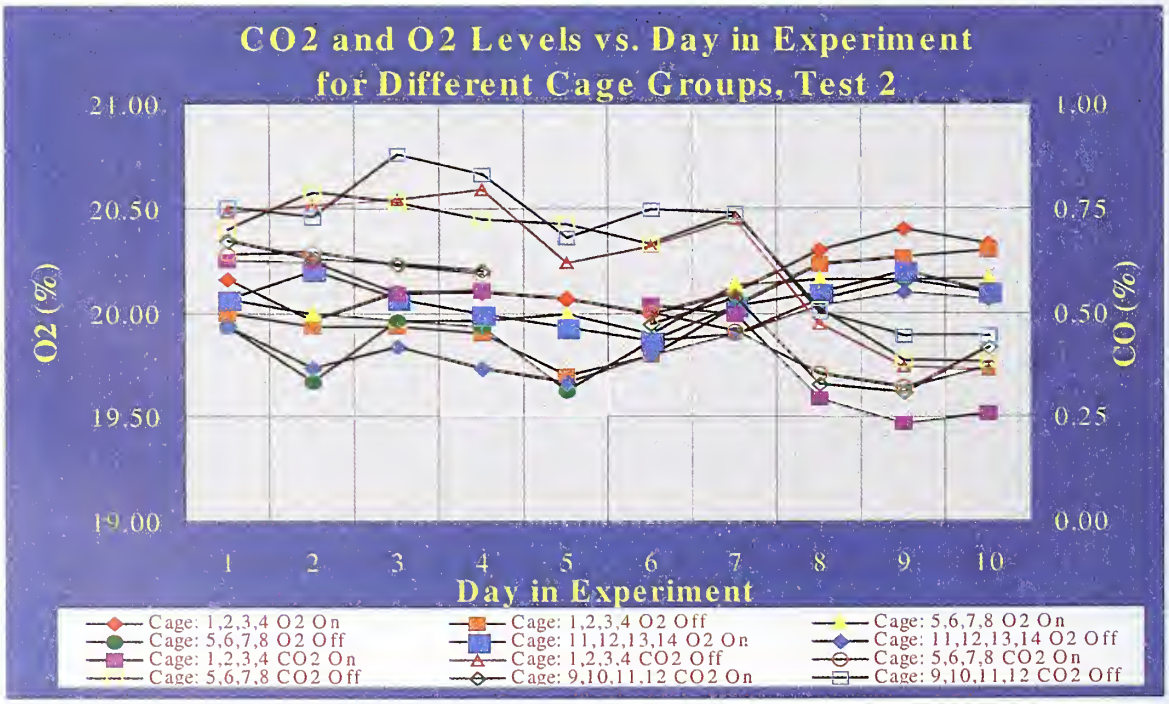

O2 Consumption and CO2 Generation Rate vs. Day in Experiment for Different Cage Groups, Test 1
O2 Consumption and CO2 Generation Rate (g/hr/ 100g body wt)
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
1 2 3 4 5 6 7 8 9 10
Day in Experiment
Cage: 1,2,3,4 O2 on
Cage: 1,2,3,4 CO2 on
Cage: 1,2,3,4 O2 off
Cage: 1,2,3,4 CO2 off
Cage: 5,6,7,8 O2 on
Cage: 5,6,7,8 CO2 on
Cage: 5,6,7,8 O2 off
Cage: 5,6,7,8 CO2 off
Cage: 9,10,11,12 O2 on
Cage: 9,10,11,12 CO2 on
Cage: 9,10,11,12 O2 off
Cage: 9,10,11,12 CO2 on

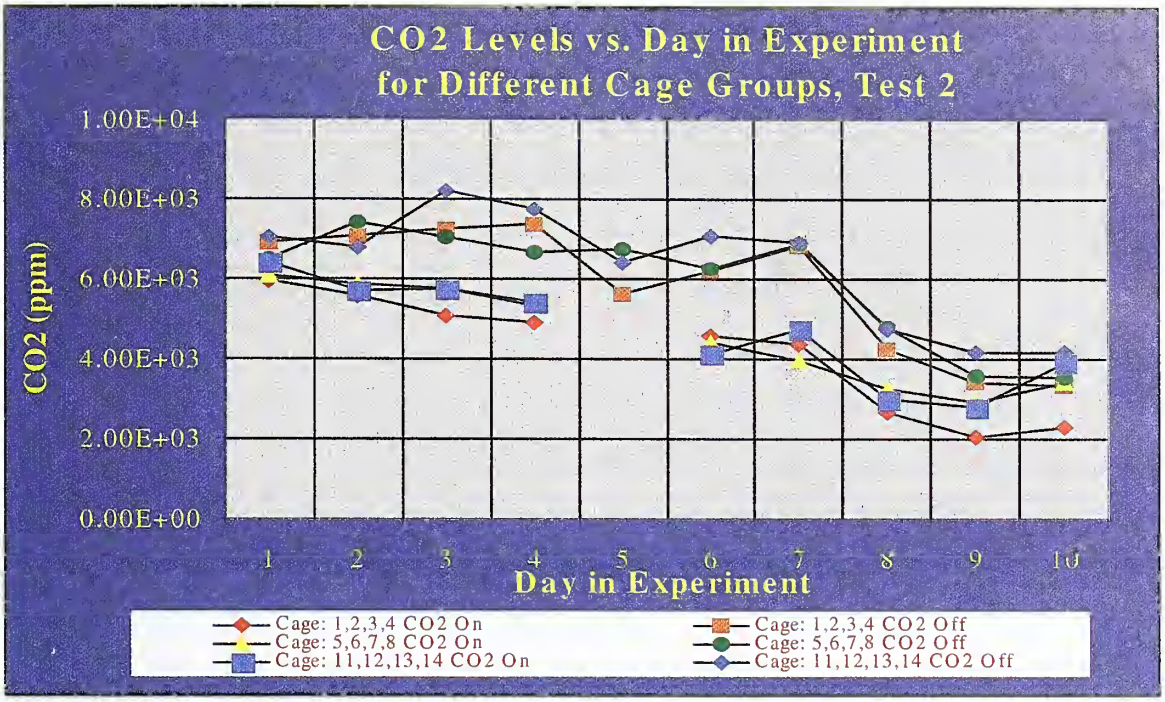


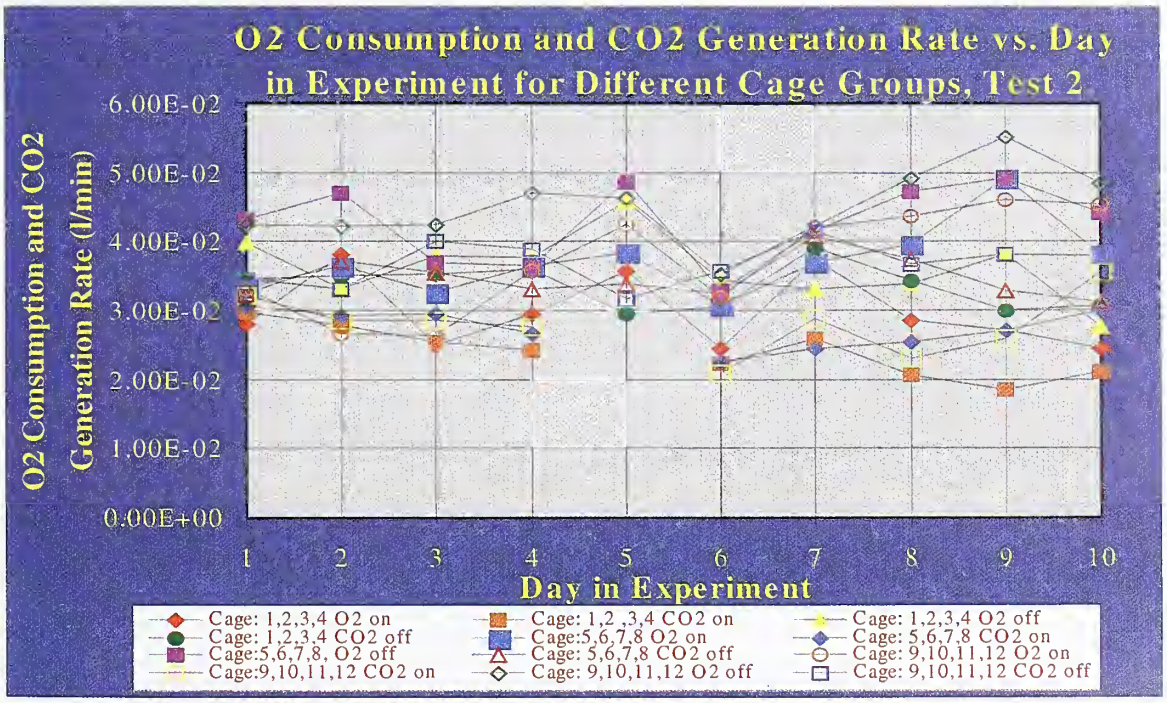
3.4.2.2 Gas Concentration and Mass Generation Rates: Individual Calorimeter Data (O_2, CO_2, and NH_3) for Test 2

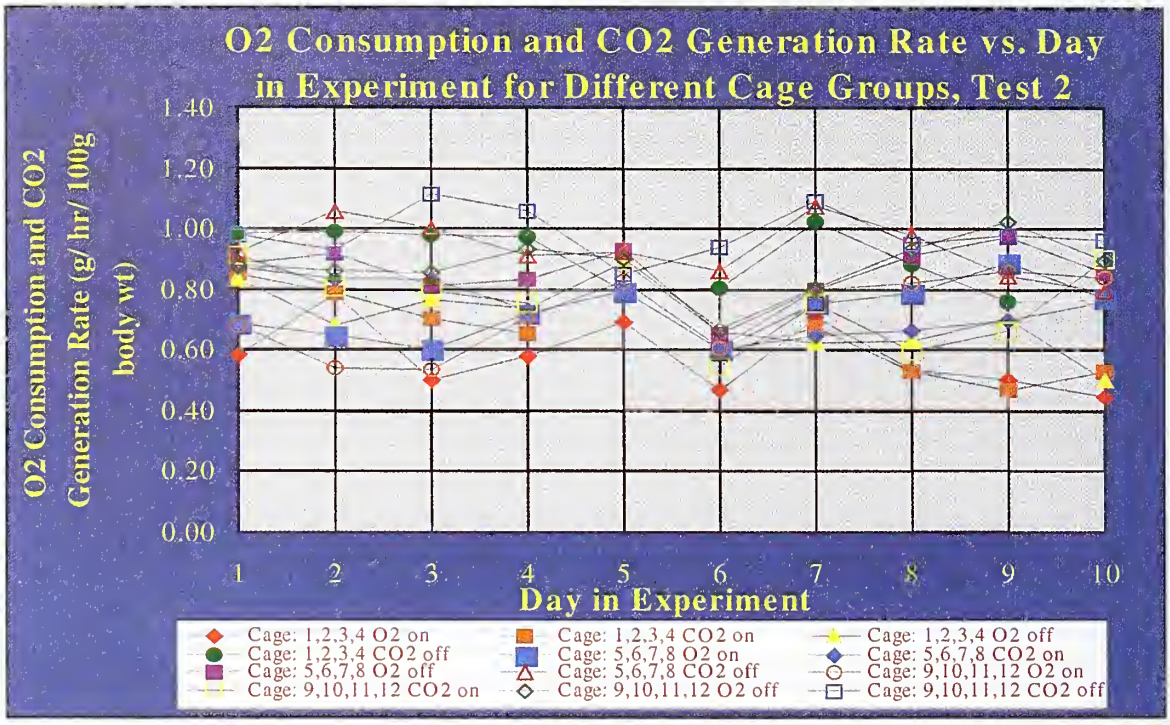


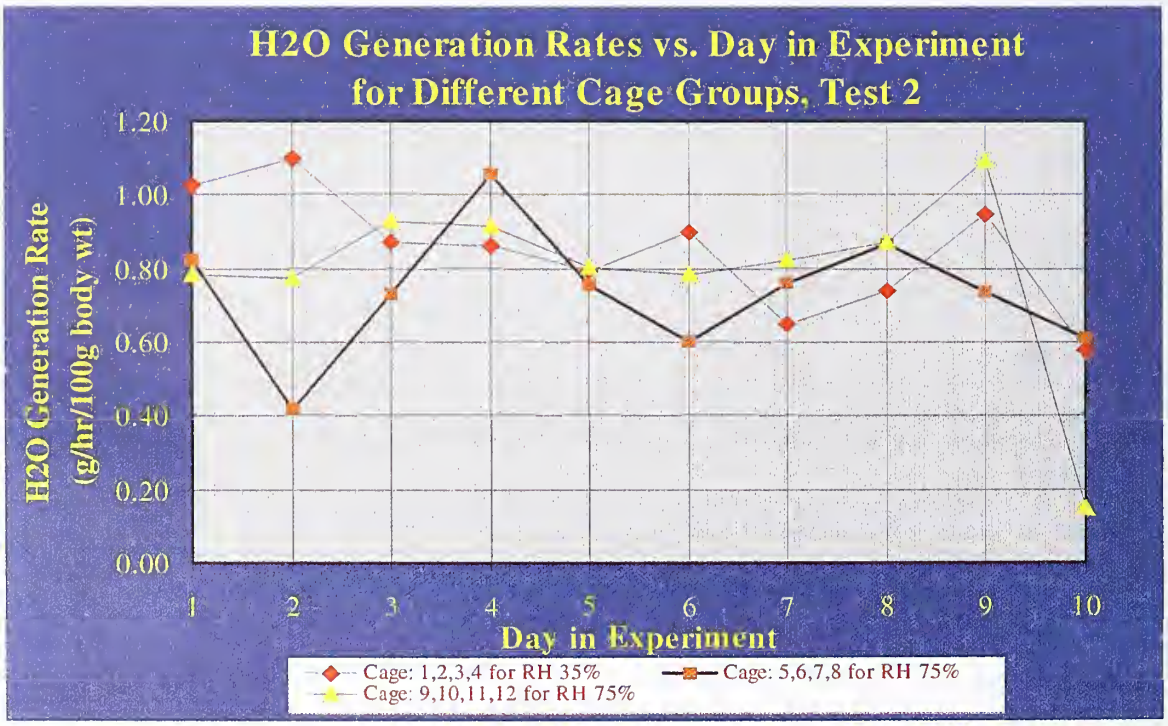

NH3 Generation Rates vs. Day in Experiment
for Different Cage Groups,Test 2
NH3 Generation Rate
(g/hr/100g body wt)
1.60E-02
1.40E-02
1.20E-02
1.00E-02
8.00E-03
6.00E-03
4.00E-03
2.00E-03
0.00E+00
1
2
3
4
5
6
7
8
9
10
Day in Experiment
Cage: 12,2,3,4 NH3 light on
Cage: 1,2 3, 4 NH3 light off
Cage: 5,6,7,8 NH3 light on
Cage: 5,6,7,8 NH3 light off
Cage: 9,10,11,12 NH3 light on
Cage: 9,10,11,12 light off


CO2 and O2 Levels vs. Day in Experiment
for Different Cage Groups, Test 2
O2 (%)
21.00
20.50
20.00
19.50
19.00
CO (%)
1.00
0.75
0.50
0.25
0.00
1
2
3
4
5
6
7
8
9
10
Day in Experiment
Cage: 1,2,3,4 O2 On
Cage: 1,2,3,4 O2 Off
Cage: 5,6,7,8 O2 On
Cage: 5,6,7,8 O2 Off
Cage: 11,12,13,14 O2 On
Cage: 11,12,13,14 O2 Off
Cage: 1,2,3,4 CO2 On
Cage: 1,2,3,4 CO2 Off
Cage: 5,6,7,8 CO2 On
Cage: 5,6,7,8 CO2 Off
Cage: 9,10,11,12 CO2 On
Cage: 9,10,11,12 CO2 Off

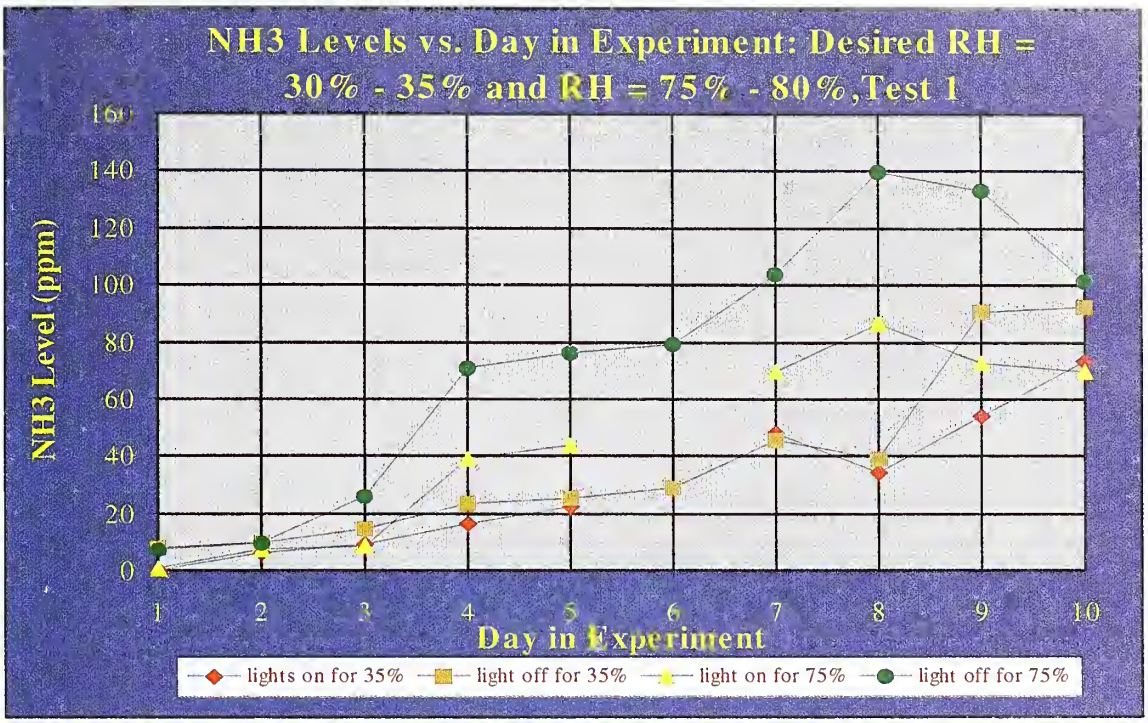

CO2 Levels vs. Day in Experiment
for Different Cage Groups, Test 2
CO2 (ppm)
1.00E+04
8.00E+03
6.00E+03
4.00E+03
2.00E+03
0.00E+00
1
2
3
4
5
6
7
8
9
10
Day in Experiment
Cage: 1,2,3,4 CO2 On
Cage: 5,6,7,8 CO2 On
Cage: 11,12,13,14 CO2 On
Cage: 1,2,3,4 CO2 Off
Cage: 5,6,7,8 CO2 Off
Cage: 11,12,13,14 CO2 Off

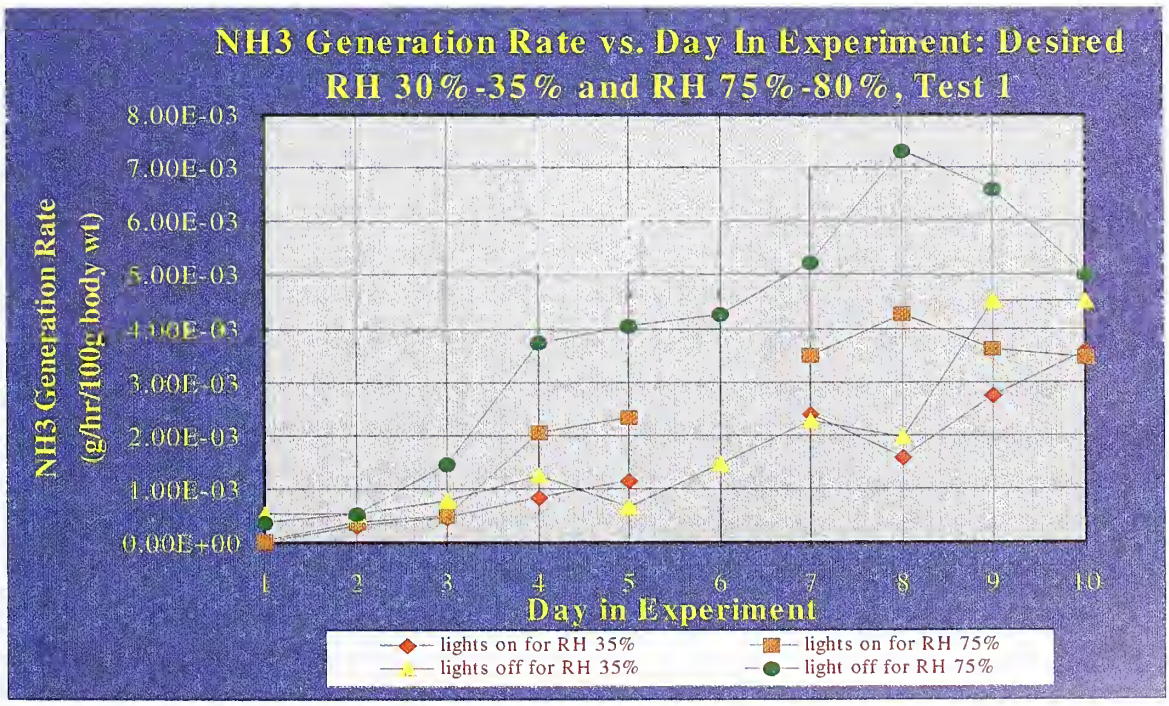

O2 Consumption and CO2 Generation Rate vs. Day
in Experiment for Different Cage Groups, Test 2
O2 Consumption and CO2
Generation Rate (l/min)
6.00E-02
5.00E-02
4.00E-02
3.00E-02
2.00E-02
1.00E-02
0.00E+00
1
2
3
4
5
6
7
8
9
10
Day in Experiment
Cage: 1,2,3,4 O2 on
Cage: 1,2,3,4 CO2 off
Cage:5,6,7,8, O2 off
Cage:9,10,11,12 CO2 on
Cage: 1,2 ,3,4 CO2 on
Cage:5,6,7,8 O2 on
Cage: 5,6,7,8 CO2 off
Cage: 9,10,11,12 O2 off
Cage: 1,2,3,4 O2 off
Cage: 5,6,7,8 CO2 on
Cage: 9,10,11,12 O2 on
Cage: 9,10,11,12 CO2 off

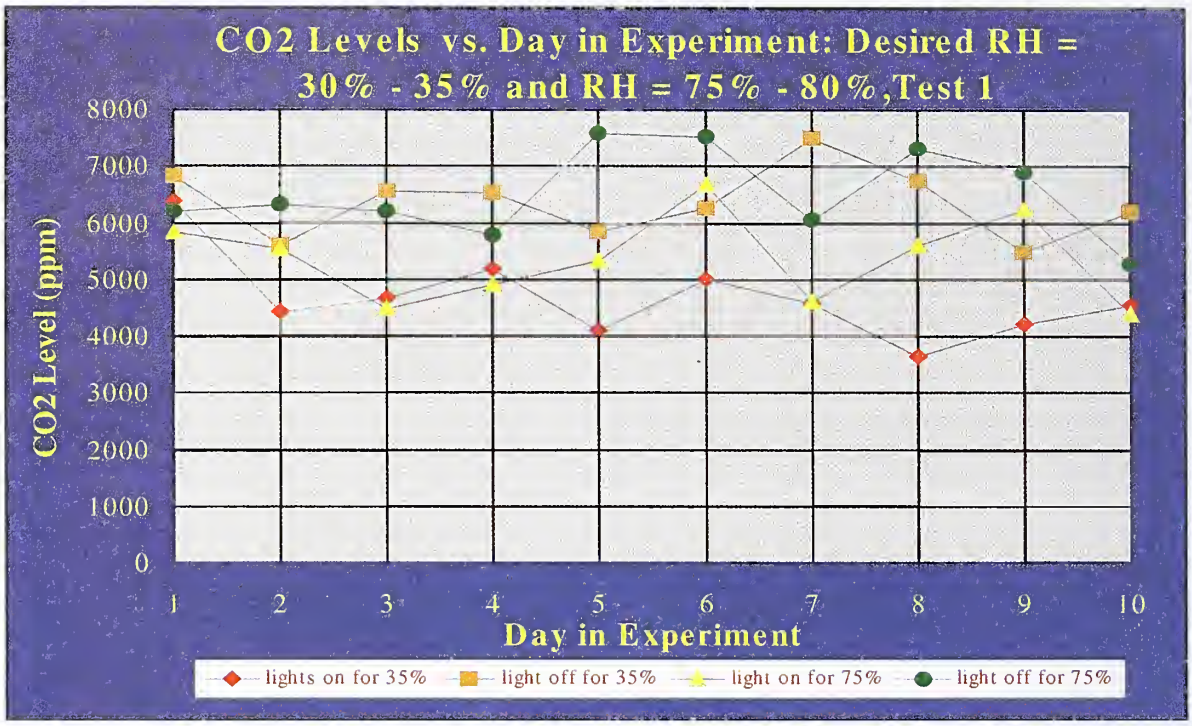

O2 Consumption and CO2 Generation Rate vs. Day in Experiment for Different Cage Groups, Test 2
O2 Consumption and CO2 Generation Rate (g/hr/100g body wt)
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
1
2
3
4
5
6
7
8
9
10
Day in Experiment
Cage: 1,2,3,4 O2 on
Cage: 1,2,3,4 CO2 on
Cage: 1,2,3,4 O2 off
Cage: 1,2,3,4 CO2 off
Cage: 5,6,7,8 O2 on
Cage: 5,6,7,8 CO2 on
Cage: 5,6,7,8 O2 off
Cage: 5,6,7,8 CO2 off
Cage: 9,10,11,12 O2 on
Cage: 9,10,11,12 CO2 on
Cage: 9,10,11,12 O2 off
Cage: 9,10,11,12 CO2 off

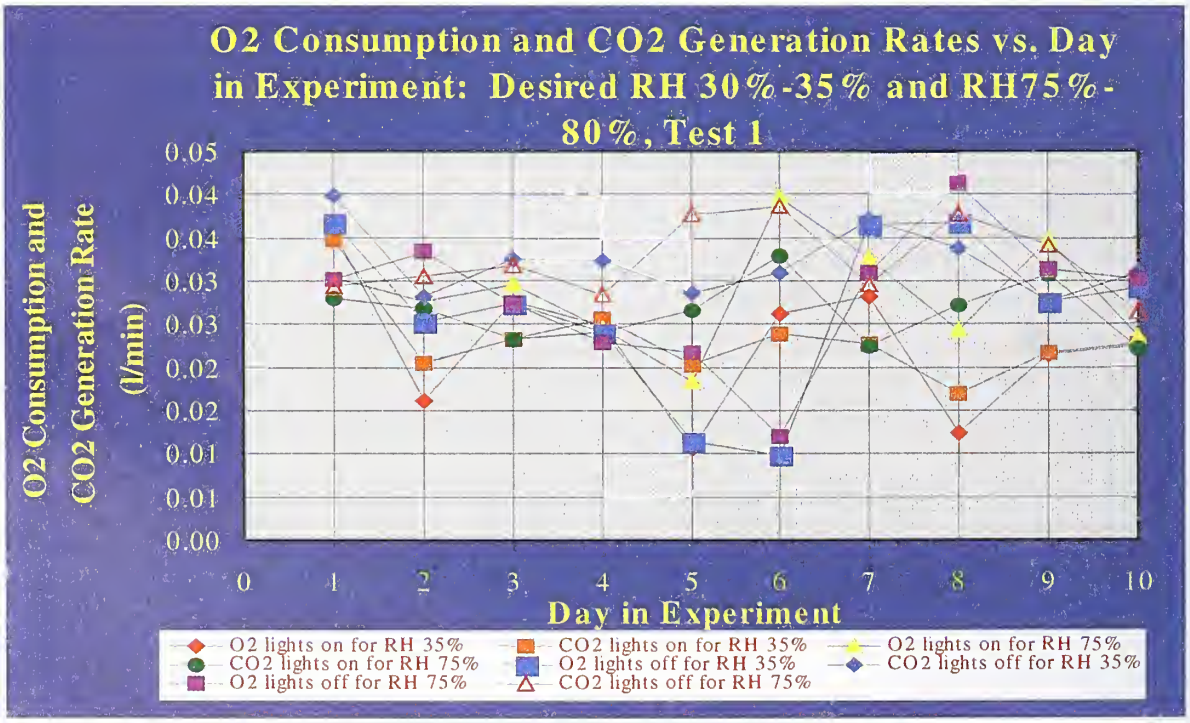

H2O Generation Rates vs. Day in Experiment for Different Cage Groups, Test 2
H2O Generation Rate (g/hr/100g body wt)
1.20
1.00
0.80
0.60
0.40
0.20
0.00
1
2
3
4
5
6
7
8
9
10
Day in Experiment
Cage: 1,2,3,4 for RH 35%
Cage: 5,6,7,8 for RH 75%
Cage: 9,10,11,12 for RH 75%

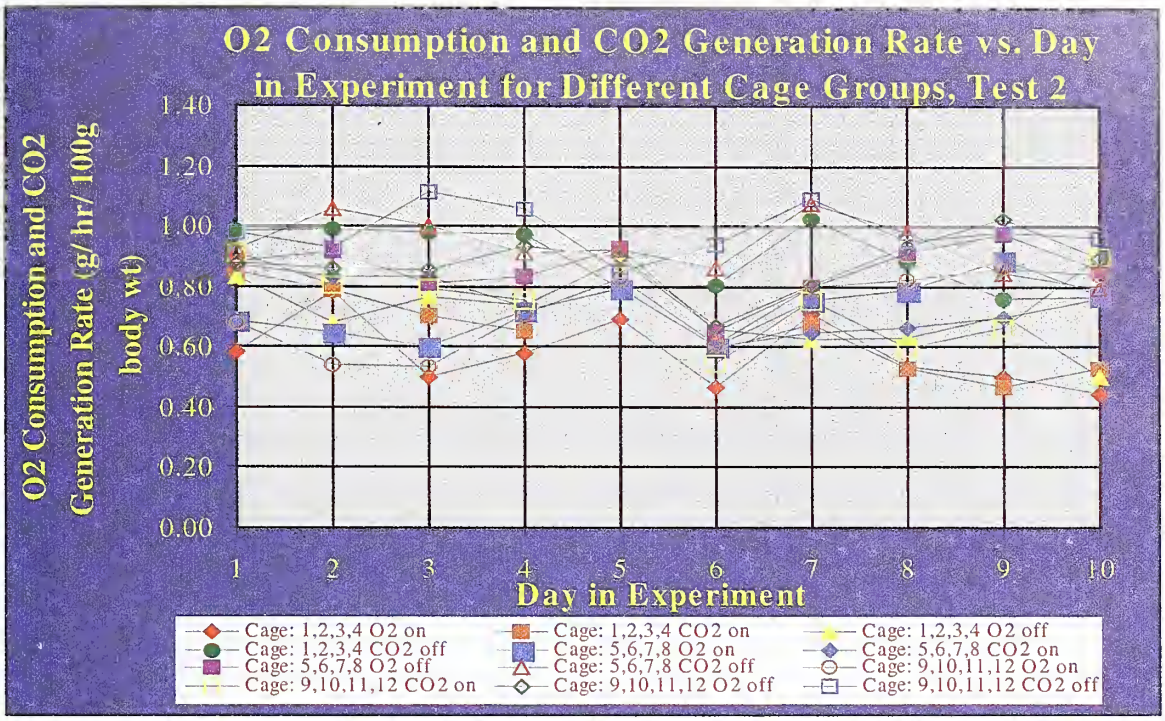
3.4.2.3 *Average Gas Mass Generation Rate for All Experimental Units in Test 1*

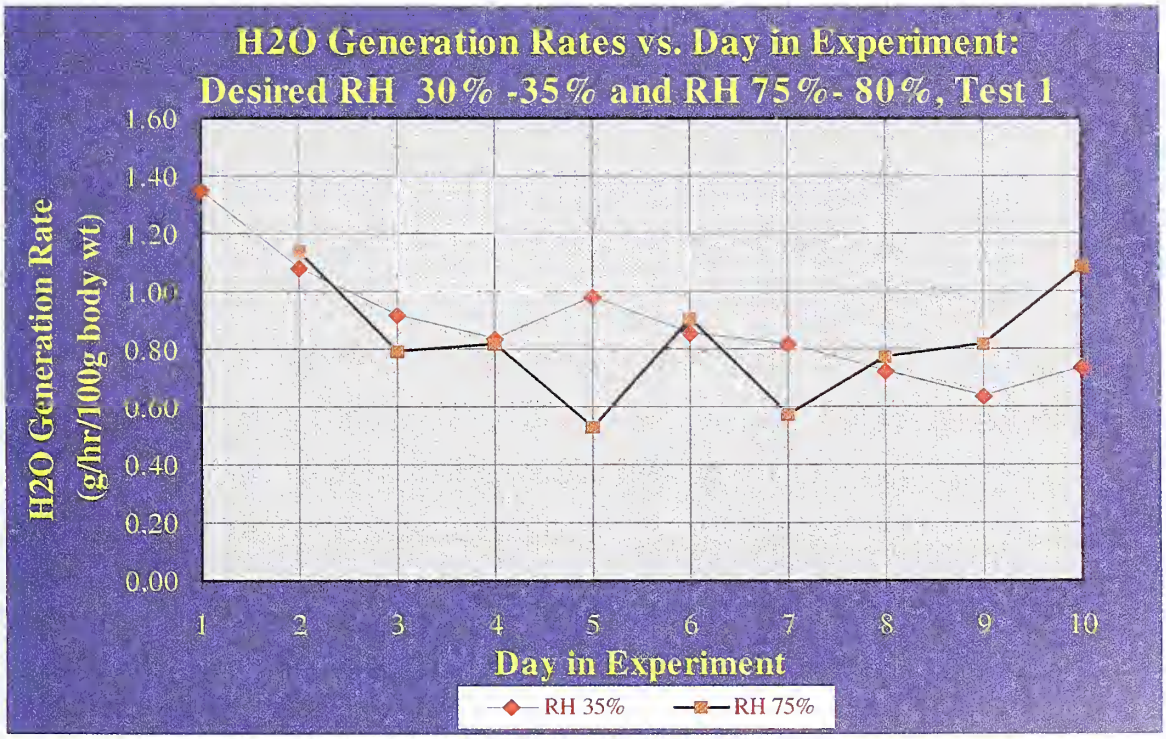




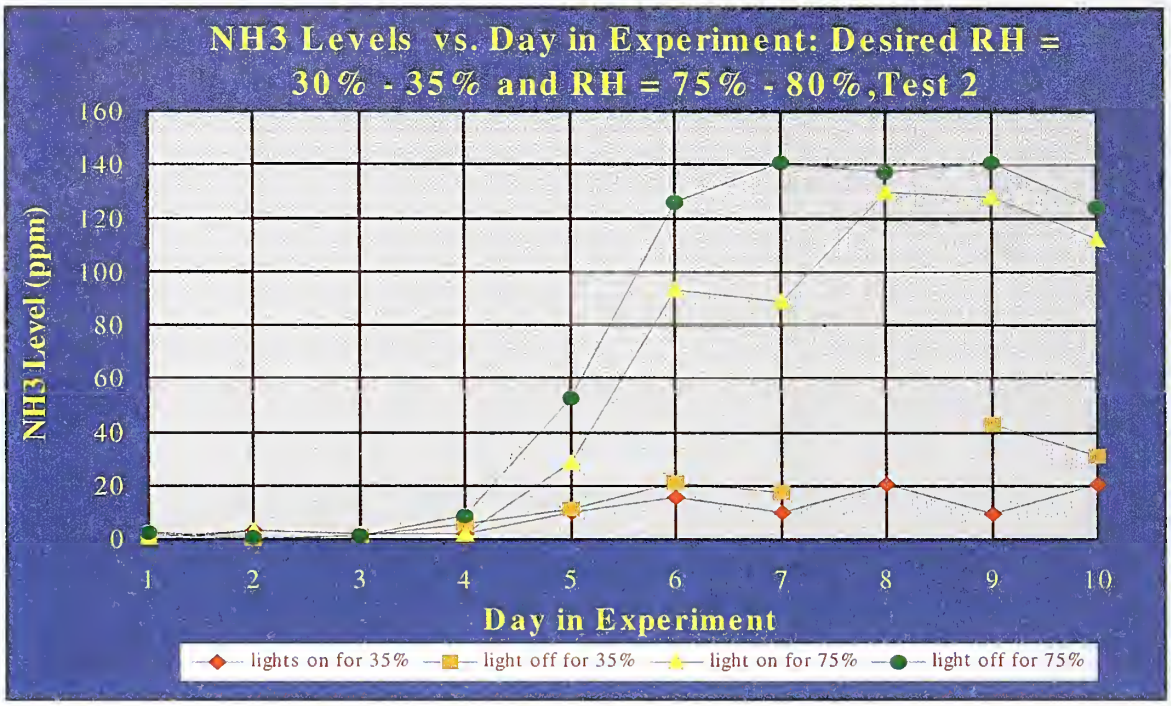

CO2 Levels vs. Day in Experiment: Desired RH = 30% - 35% and RH = 75% - 80%,Test 1
CO2 Level (ppm)
8000
7000
6000
5000
4000
3000
2000
1000
0
1
2
3
4
5
6
7
8
9
10
Day in Experiment
lights on for 35%
light off for 35%
light on for 75%
light off for 75%

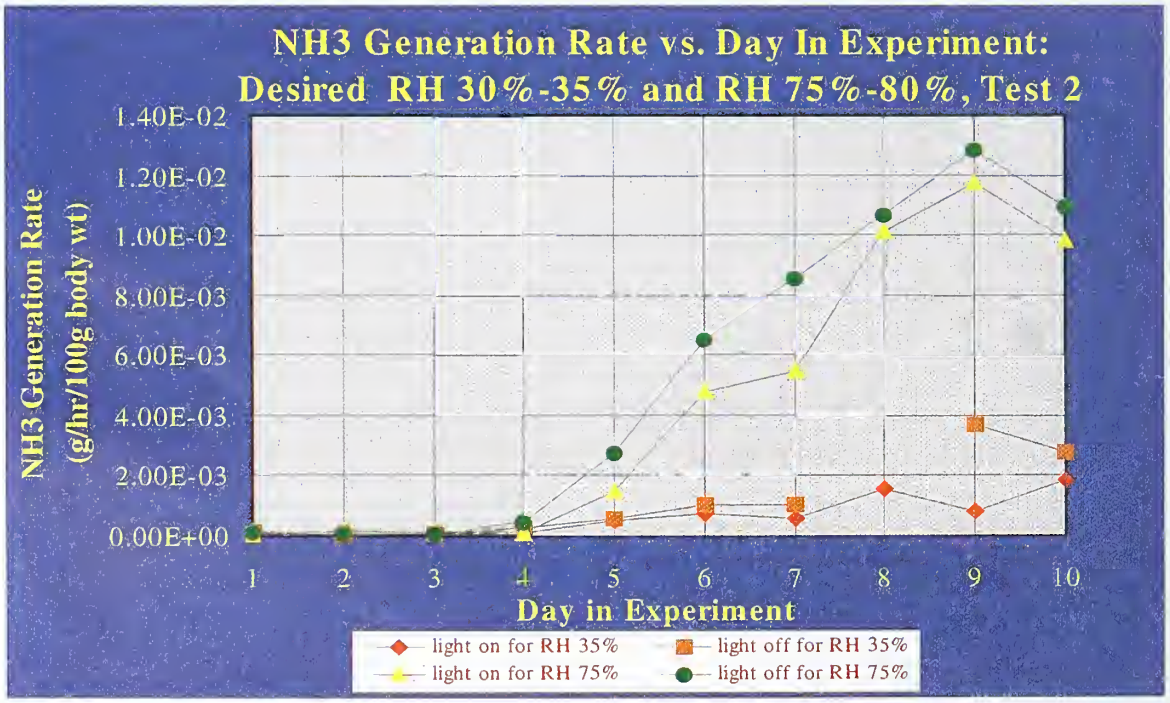

O2 Consumption and CO2 Generation Rates vs. Day in Experiment: Desired RH 30%-35% and RH75%-80%, Test 1
O2 Consumption and CO2 Generation Rate (l/min)
0.05
0.04
0.04
0.03
0.03
0.02
0.02
0.01
0.01
0.00
0
1
2
3
4
5
6
7
8
9
10
Day in Experiment
O2 lights on for RH 35%
CO2 lights on for RH 35%
O2 lights on for RH 75%
CO2 lights on for RH 75%
O2 lights off for RH 35%
CO2 lights off for RH 35%
O2 lights off for RH 75%
CO2 lights off for RH 75%

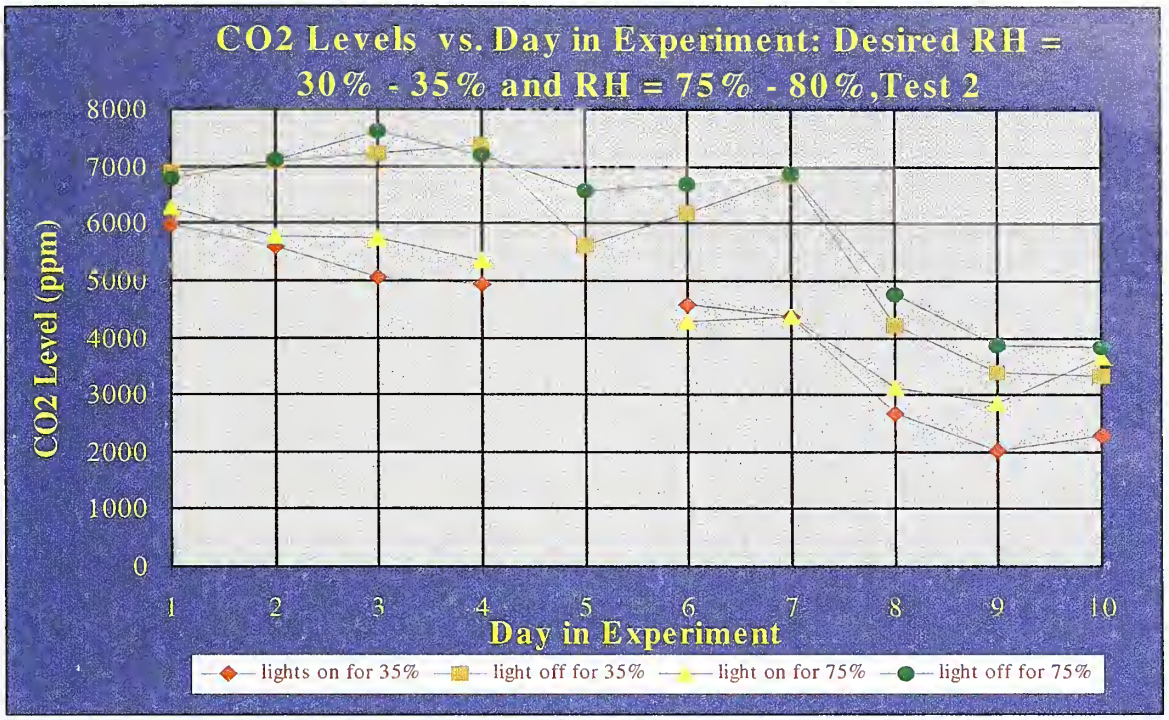

O2 Consumption and CO2 Generation Rate vs. Day in Experiment for Different Cage Groups, Test 2
O2 Consumption and CO2 Generation Rate (g/ hr/ 100g body wt)
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
1
2
3
4
5
6
7
8
9
10
Day in Experiment
Cage: 1,2,3,4 O2 on
Cage: 1,2,3,4 CO2 on
Cage: 1,2,3,4 O2 off
Cage: 1,2,3,4 CO2 off
Cage: 5,6,7,8 O2 on
Cage: 5,6,7,8 CO2 on
Cage: 5,6,7,8 O2 off
Cage: 5,6,7,8 CO2 off
Cage: 9,10,11,12 O2 on
Cage: 9,10,11,12 CO2 on
Cage: 9,10,11,12 O2 off
Cage: 9,10,11,12 CO2 off

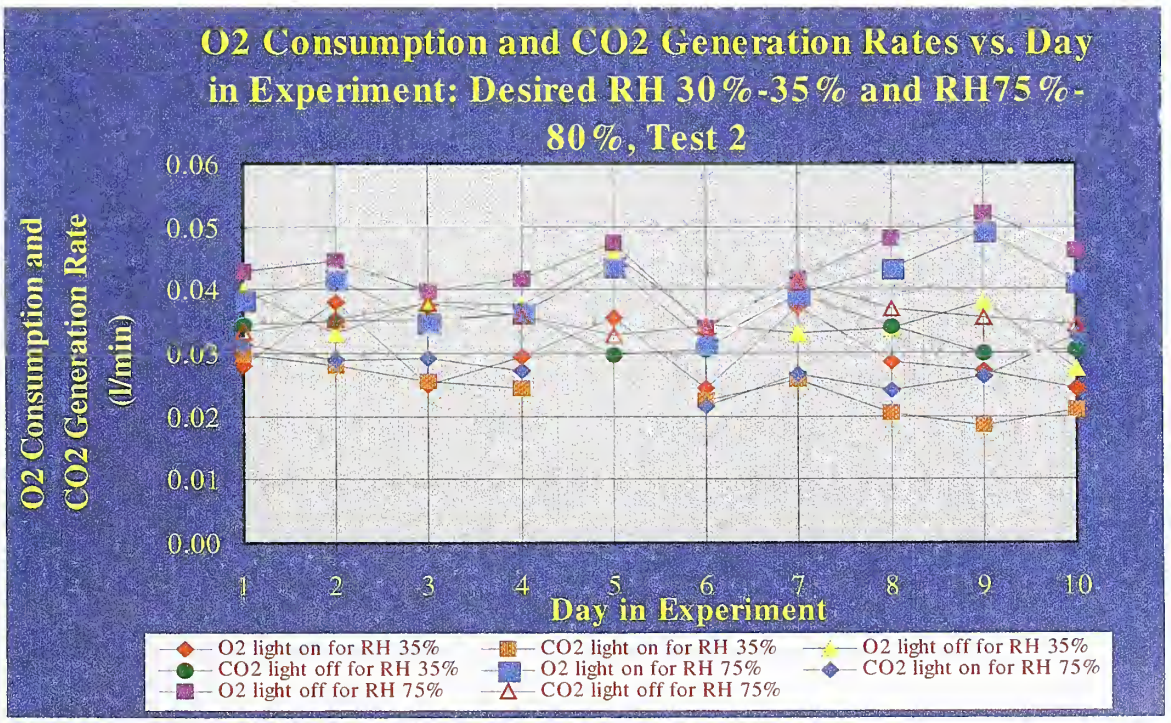

H2O Generation Rates vs. Day in Experiment: Desired RH 30% -35% and RH 75%- 80%, Test 1
H2O Generation Rate (g/hr/100g body wt)
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
1
2
3
4
5
6
7
8
9
10
Day in Experiment
RH 35%
RH 75%

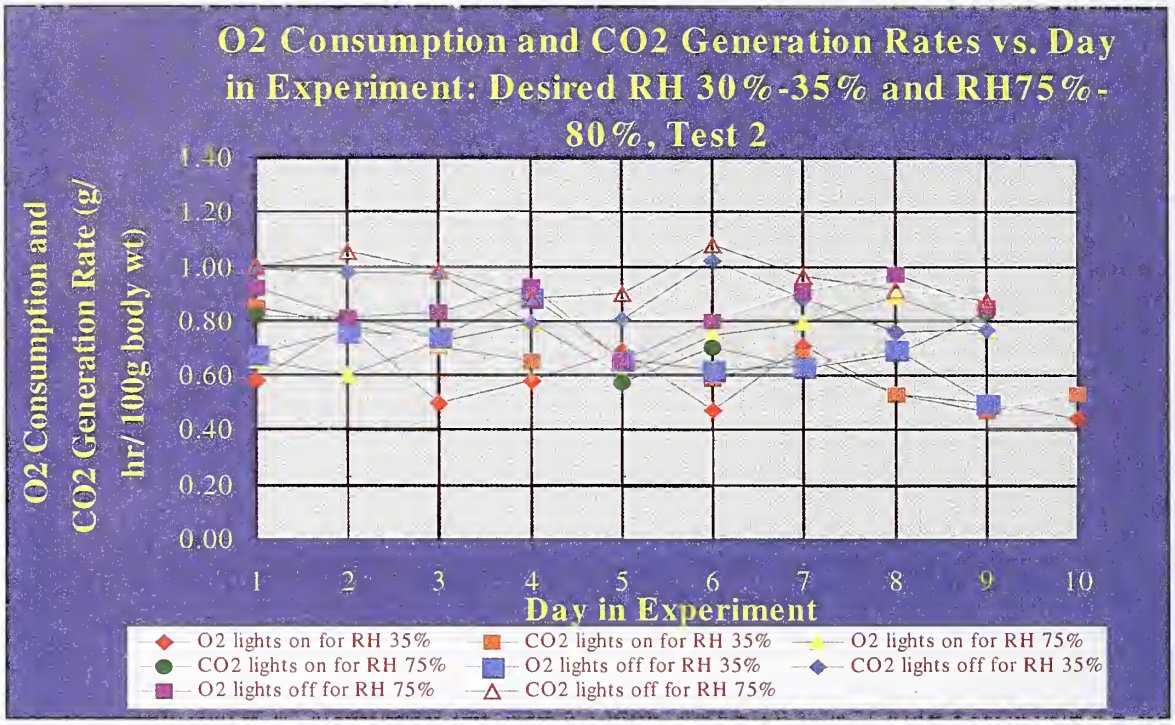
3.4.2.4 Average Gas Mass Generation Rate for All Experimental Units in Test 2

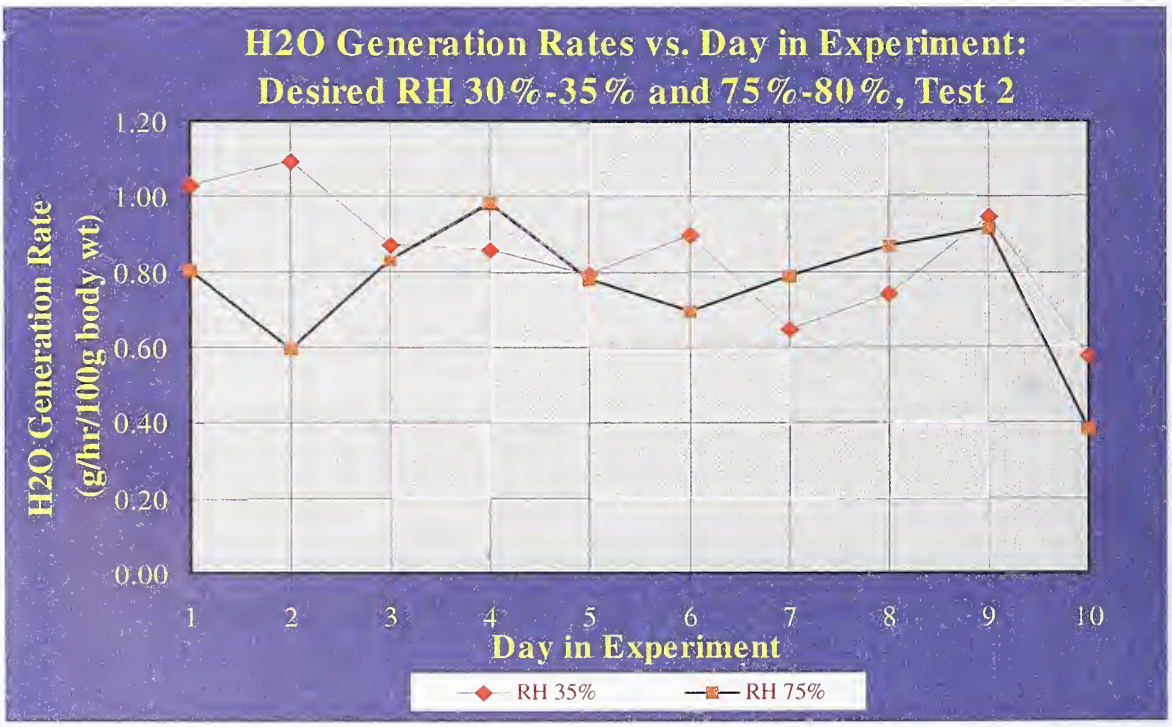




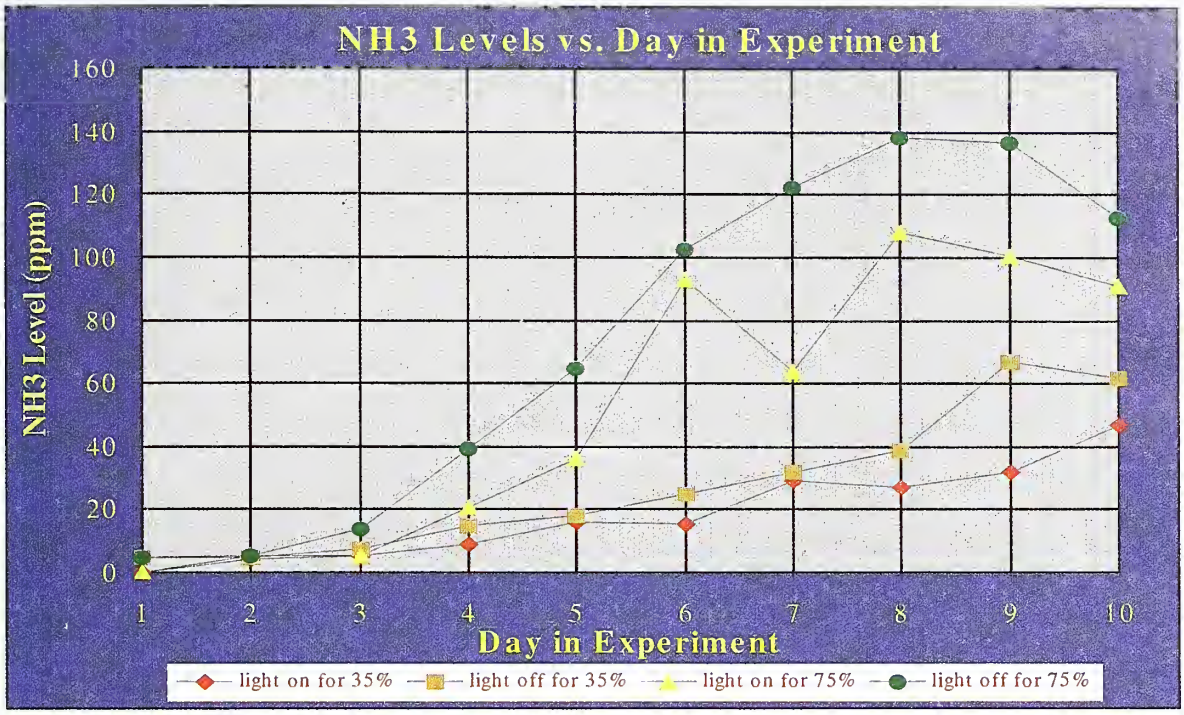

CO2 Levels vs. Day in Experiment: Desired RH = 30% - 35% and RH = 75% - 80%,Test 2
CO2 Level (ppm)
8000
7000
6000
5000
4000
3000
2000
1000
0
1
2
3
4
5
6
7
8
9
10
Day in Experiment
lights on for 35%
light off for 35%
light on for 75%
light off for 75%

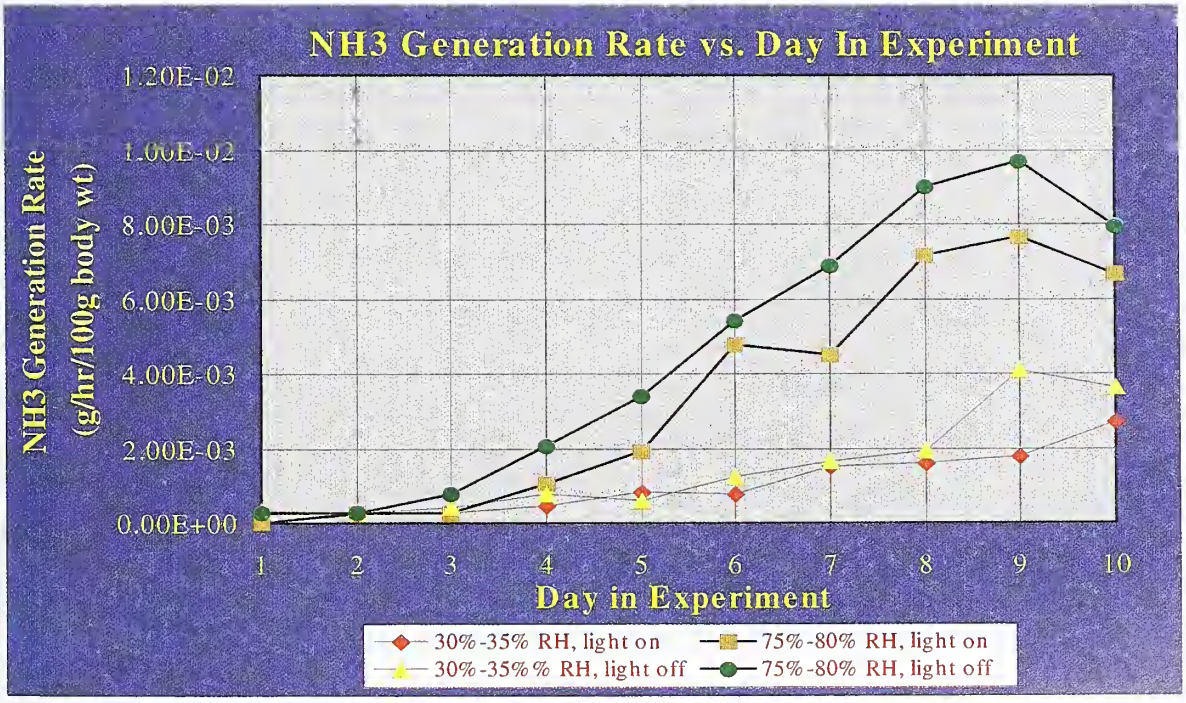

O2 Consumption and CO2 Generation Rates vs. Day in Experiment: Desired RH 30%-35% and RH75%-80%, Test 2
O2 Consumption and CO2 Generation Rate (l/min)
0.06
0.05
0.04
0.03
0.02
0.01
0.00
1
2
3
4
5
6
7
8
9
10
Day in Experiment
O2 light on for RH 35%
CO2 light on for RH 35%
O2 light off for RH 35%
CO2 light off for RH 35%
O2 light on for RH 75%
CO2 light on for RH 75%
O2 light off for RH 75%
CO2 light off for RH 75%

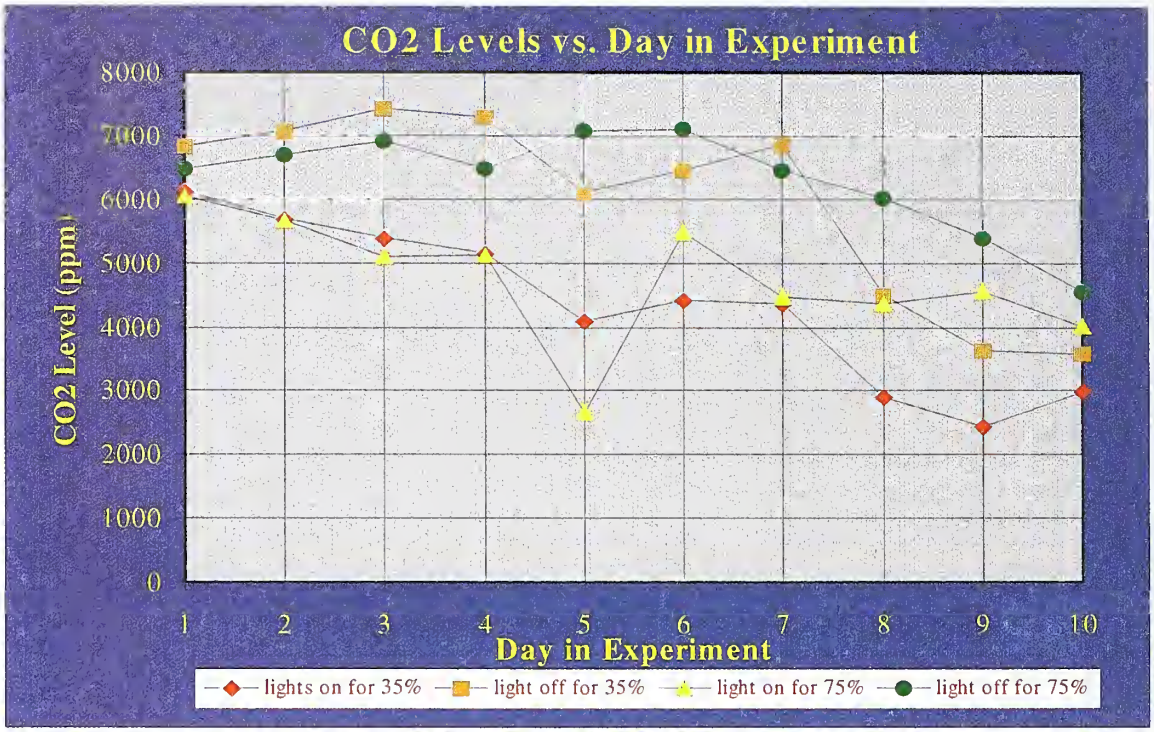

O2 Consumption and CO2 Generation Rates vs. Day in Experiment: Desired RH 30%-35% and RH75%-80%, Test 2
O2 Consumption and CO2 Generation Rate (g/hr/100g body wt)
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
1 2 3 4 5 6 7 8 9 10
Day in Experiment
O2 lights on for RH 35%
CO2 lights on for RH 35%
O2 lights on for RH 75%
CO2 lights on for RH 75%
O2 lights off for RH 35%
CO2 lights off for RH 35%
O2 lights off for RH 75%
CO2 lights off for RH 75%

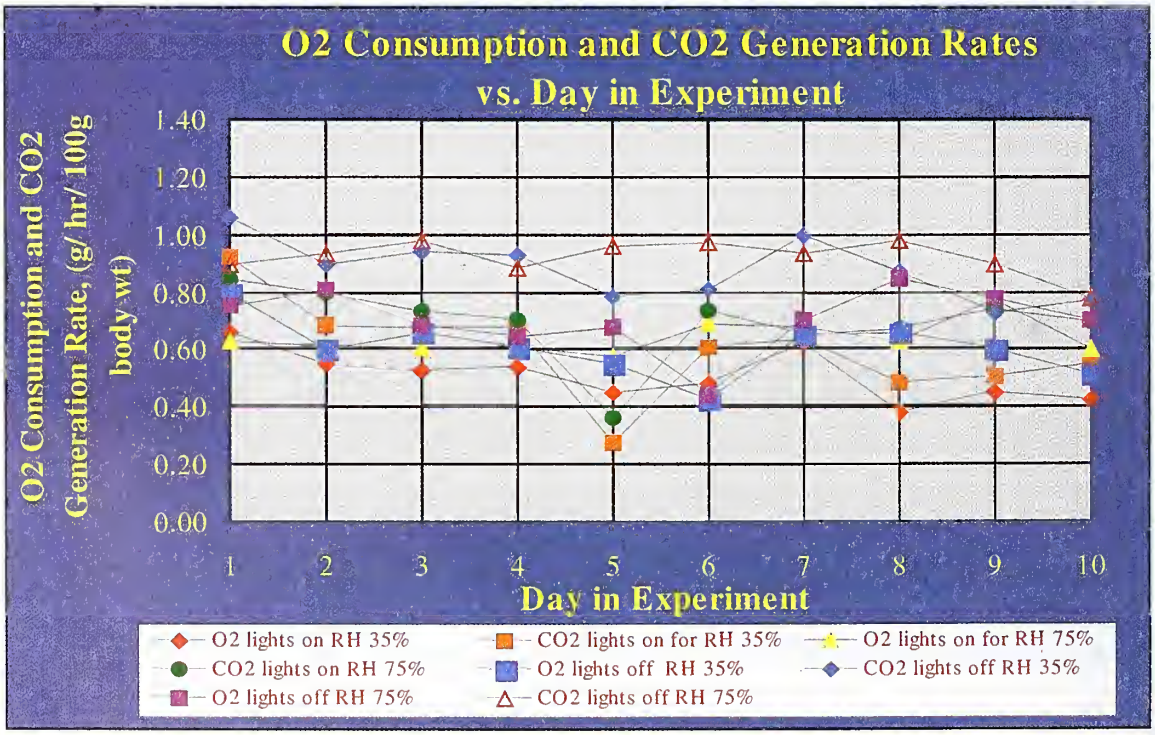

H2O Generation Rates vs. Day in Experiment: Desired RH 30%-35% and 75%-80%, Test 2
H2O Generation Rate (g/hr/100g body wt)
1.20
1.00
0.80
0.60
0.40
0.20
0.00
1 2 3 4 5 6 7 8 9 10
Day in Experiment
RH 35%
RH 75%

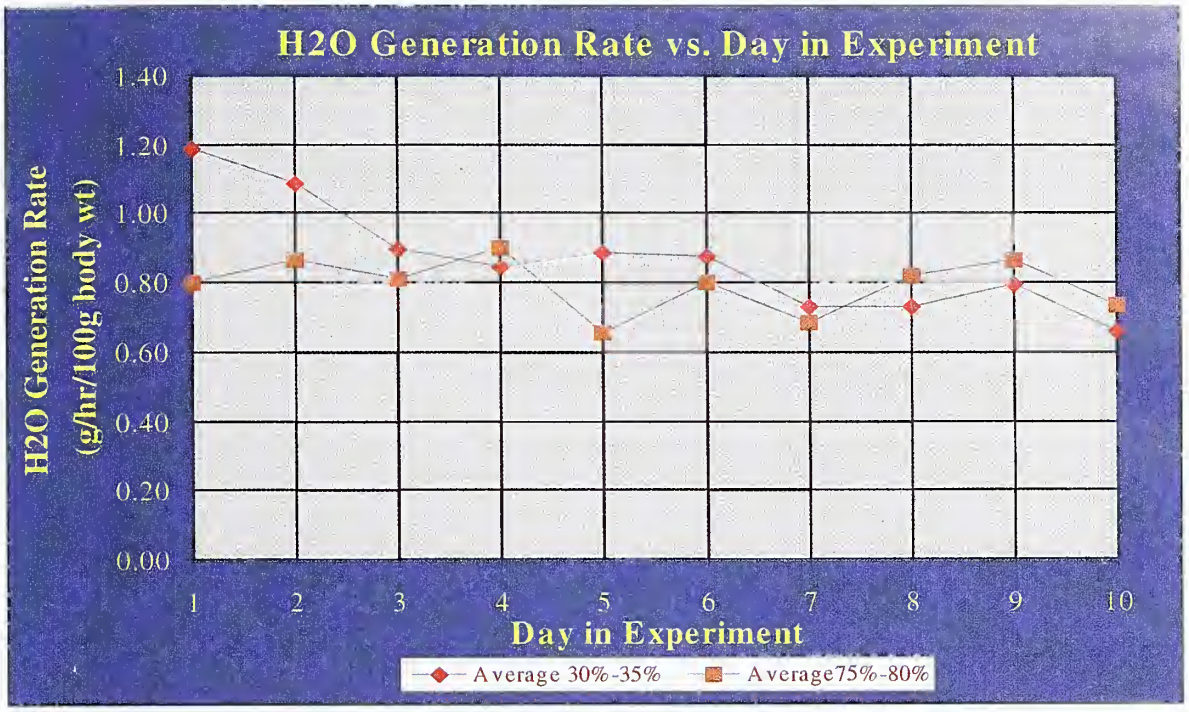
3.4.2.5 Averaged Data for All Experimental Units from Test 1 and Test 2



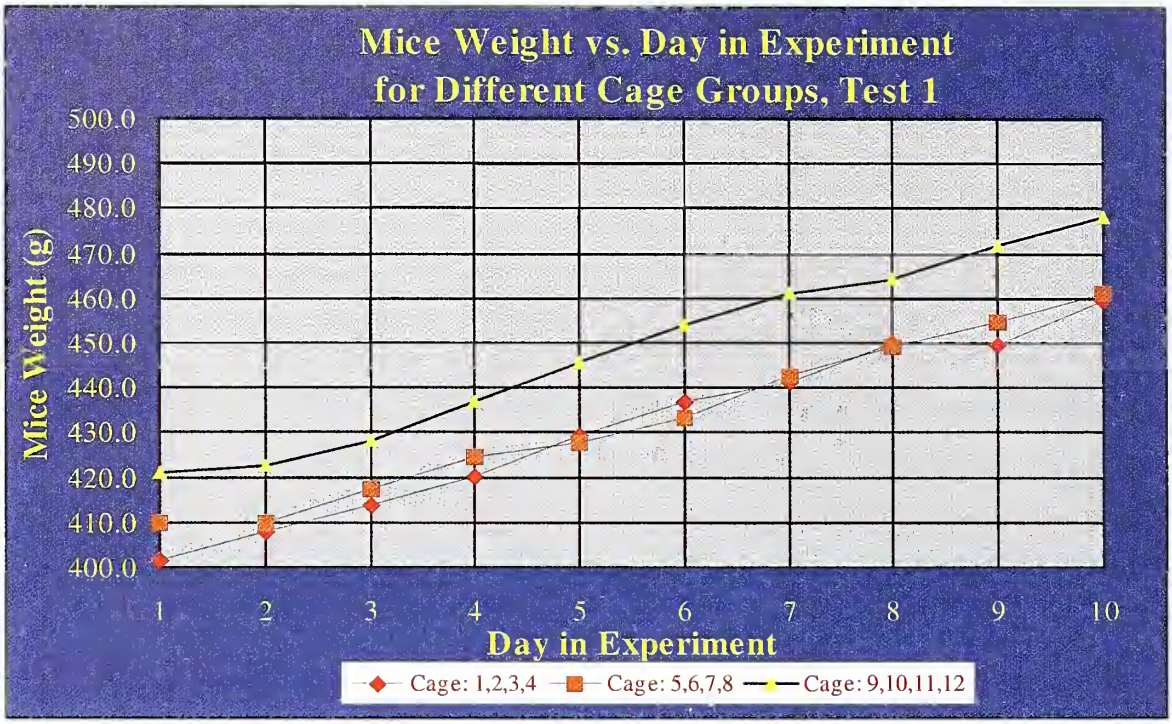


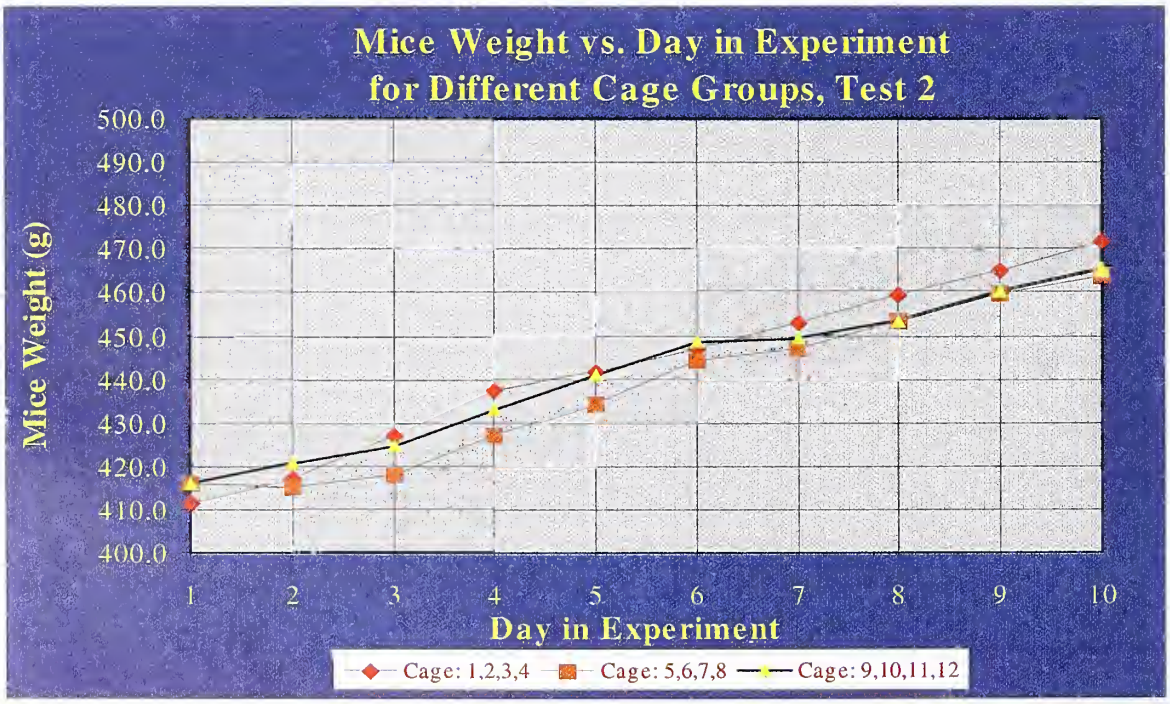

CO2 Levels vs. Day in Experiment
CO2 Level (ppm)
8000
7000
6000
5000
4000
3000
2000
1000
0
1
2
3
4
5
6
7
8
9
10
Day in Experiment
lights on for 35%
light off for 35%
light on for 75%
light off for 75%


O2 Consumption and CO2 Generation Rates vs. Day in Experiment
O2 Consumption and CO2 Generation Rate, (g/ hr/ 100g body wt)
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
1
2
3
4
5
6
7
8
9
10
Day in Experiment
O2 lights on RH 35%
CO2 lights on for RH 35%
O2 lights on for RH 75%
CO2 lights on RH 75%
O2 lights off RH 35%
CO2 lights off RH 35%
O2 lights off RH 75%
CO2 lights off RH 75%


H2O Generation Rate vs. Day in Experiment
H2O Generation Rate
(g/hr/100g body wt)
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
1
2
3
4
5
6
7
8
9
10
Day in Experiment
Average 30%-35%
Average75%-80%

3.4.2.6 Mice Weights for Different Groups for Tests 1 and 2





4. ROOM CONDITION

4.1 Justification of Air Velocity Sampling Frequency

4.1.1 Minimum Sampling Frequency

To measure the turbulence intensity in an airflow field, air velocity sampling frequency must be sufficiently high so that the original air velocity fluctuation patterns can be reconstructed. The minimum sampling frequency (f_s) should be twice as much as the fluctuation frequency of the measured variable (f_v), air velocity in this case, i.e.,

$$f_s > 2 f_v \qquad (4.1)$$

The fluctuation frequency of air velocity is affected by at least the following factors: air velocity, boundary conditions of the airflow field, and the jet momentum. In this study, there are two subzones: jet zone or Zone 2 (within 0.30m (12") of the diffuser) and occupied zone or Zone 1 (the rest of the room airspace).

4.1.2 Air Velocity of Jet Zone and Occupied Zone

For the jet zone, the air discharge from the perforated diffuser is a free jet. Thus, only the discharge velocity and the jet momentum are considered to be key factors affecting the turbulence intensity.

For the given perforated diffuser, the diameter of each discharge hole is 2.38e-3m (3/32"). There are 10,890 holes with a total discharge opening of 4.85 m^2 (0.52 ft^2). The dimension of the diffuser discharging area is 0.38m^2 (4.13 ft^2) (0.69m (27") long and 0.56m (22") wide)). The air supply rate is 10 air changes per hour (ACH) which is 6.04e-2 m^3/s (128 cfm). Because the effect of the vena contracta, the effective discharge opening is smaller than the actual area of the hole. This effect can be accounted for by applying a discharge coefficient C_d. Considering the flow as a flow in a virtual cylinder before being discharged from the hole, the area ratio A_2 to A_1 is 12.7 percent, the same as the opening ratio of the diffuser, where A_2 is the opening area of hole, and A_1 is the cross-section area of the virtual cylinder. Thus the ratio of D_2 to D_1 is 0.36 and the *Cd* is 0.6 (McQuiston and Parker, 1977). Thus the mean discharge air velocity from each hole is

$$\begin{aligned} U_i &= 128/(C_d \Sigma A_2) \\ &= 128/(0.6 \bullet 0.522) = 409 \ fpm \end{aligned} \qquad (4.2)$$

Since this discharge velocity from the free jet has a very small momentum, the air velocity will attenuate quickly. Using the free jet theory, the jet velocity (U_x) at a distance (x) from the discharge opening is given by (Wilson, Ed: Hellickson and Walker, 1983)

$$U_x = 7.6\, U_i\, A/x \qquad (4.3)$$

Where A is the opening area of the jet: 0.0000479 ft^2.

The first measurement point is two inches from the diffuser. The vena contracta from the discharging surface is less than 0.5 $D_2 = 3/64$" and therefore is negligible compared with the x. At 5.0e-2m (2") distance from the opening, the air jet velocity will be reduced to

$$U\big/_{x=2''} = 7.6 \bullet 409 \bullet 0.0000479^{1/2} \div 0.1667 = 129\, fpm \qquad (4.4)$$

Thus, the air velocity will not exceed 129 fpm at any measurement point in the jet zone (Zone 2) unless the airflow field is disturbed. Compared with the conventional air diffusers, the air velocity of this perforated diffuser is very low, and hence, low turbulence intensities.

At an outside measurement point in the jet zone (x = 12"), the jet velocity will be:

$$U\big/_{x=12''} = 7.6 \bullet 409 \bullet 0.0000479^{1/2} \div 1 = 22\, fpm \qquad (4.5)$$

Thus, on average, the air velocity will not exceed 22 fpm at any measurement point in the occupied zone (Zone 1), except in vicinity of the exhaust outlet, unless the airflow field is disturbed.

4.1.3 Air Velocity Fluctuation in the Jet Zone

Air velocities in a jet zone of a room air space have a strong random feature. The air velocities in the jet zone contains more high fluctuation frequencies and more turbulence compared to those in occupied zones (Zhang, 1991). Using a hot wire anemometer and at a sampling frequency of 250 Hz, figures 4.1.01 and 4.1.02 (Zhang, 1991) illustrate examples of air velocity fluctuations in jet zones with a discharge velocity (U_d) of 350 fpm and 150 fpm, respectively.

Within each primary velocity fluctuation cycle (time period between two peak to peak values), there are high frequency fluctuations containing negligible energy that can be considered to be secondary velocity fluctuation. By the definition of the turbulence intensity, which is the ratio of the standard deviation of velocity fluctuations to the mean velocity, the secondary velocity fluctuation has only negligible influence on the turbulence intensity, i.e., the secondary high frequency fluctuations contribute very little to the overall variation of the velocity fluctuation. This can be further explained in the following example.

If the secondary velocity fluctuation were filtered out, the velocities in figures 4.1.01 and 4.1.02 can be reconstructed as in figure 4.1.03, which only contains the primary velocity fluctuation. The turbulence intensities yielded from figures 4.1.01 and 4.1.03 will be approximately the same. From figure 4.1.03, the primary velocity fluctuations have a frequency of 3.7 Hz for U_d = 350 fpm and 3.5 Hz for U_d = 150 fpm. Therefore, the velocity fluctuation frequency (f_v) for U_d = 350 fpm can be considered as 4 Hz (>3.7).

It has been proven that the energy density in a turbulent flow attenuates quickly at high frequencies (typically higher than 10 Hz). The relationship between the energy density and the frequency of the air velocity fluctuation is approximately in the order of $f_v^{-5/3}$ (Hinze, 1975). Examples of energy density spectra of air velocities are shown in figures 4.1.04 and 4.1.05 (Zhang, 1991). In the case of figure 4.1.01, in which the sampling frequency was 250 Hz, the secondary velocity fluctuation had a frequency of approximately 60 Hz. Compared with the primary velocity fluctuations at approximately 4 Hz, the energy density (E_d) in the secondary velocity fluctuation, a negligible fluctuation, was:

$$\frac{E_d|_{f=60}}{E_d|_{f=4}} = \frac{60^{-5/3}}{4^{-5/3}} = 1\%$$

Other error sources such as anemometer time response and instrumentation accuracy are usually well over 1 percent of error range and should be greater concerns than the secondary high frequency velocity fluctuations.

Since the air jet in this study has a discharge velocity of 282 fpm (from Eqn. 4.2), which is less than 350 fpm and has a much smaller jet momentum than that in figure 4.1.01, the velocity fluctuation frequency should be smaller than 4 Hz. Therefore, a sampling frequency of

$$f_s > 2f_v = 8 \ (Hz) \qquad (4.6)$$

should be sufficiently high for this application. Thus, an anemometer with a time response of less than 0.125s is required, i.e., the anemometer should be capable of sampling 8 times per second. The BERL thermister type anemometer is capable of measuring velocity fluctuations at 20 Hz sampling frequency. This thermister omni-directional anemometer was compared with two commercially available anemometers: a hot wire anemometer (TSI, model IFA 100) and an omni-directional anemometer (TSI, model 8470-13E-V).

Comparison results are shown in figures 4.1.06 and 4.1.07. The thermister and the TSI hot wire anemometer yielded approximately the same results (figures 4.1.07 to 4.1.09), but the TSI omni-directional anemometer could only respond at very low frequencies. From figure 4.1.07, the thermister anemometer responds to the velocity within 0.5 percent of error what the TSI hot wire anemometer does when the air velocity is higher than 20 fpm. In figures 4.1.08 and 4.1.09, the thermister anemometer gives a very similar frequency response to that of the TSI hot wire anemometer. These data show that the thermister omni-directional anemometer is suitable for this application.

4.1.4 Verification Using the TSI-IFA Hot Wire Anemometer

Air velocity fluctuations were measured using a fast response TSI IFA-100 anemometer. The IFA-100 is capable of measuring air velocity fluctuations up to 5,000 Hz. Due to the turbulence nature of the air diffuser, most of the energy of the airflow is carried by the low frequency (less than 5 Hz) flows. Figures 4.1.10, 4.1.11, and 4.1.12 show the airflow fluctuation patterns using sampling frequency 100, 40, and 20 Hz, respectively, within 2.5 second sampling period. Statistical comparisons of these three sampling frequencies are show in table 4.1.01.

Table 4.1.01 Statistics of air velocity fluctuations at sampling frequencies 100, 40, and 20 Hz.

	Sampling Frequency		
	100 Hz	**40 Hz**	**20 Hz**
Mean air velocity (fpm)	263.1	264.3	265.5
Turbulence intensity	0.123	0.124	0.129

The differences in mean air velocity were less than 0.5 percent between 100 Hz and 40 Hz; less than 1 percent between 100 Hz and 20 Hz; and less than 0.5 between 40 Hz and 20 Hz. The differences in turbulence intensity were 0.8 percent between 100 Hz and 40 Hz; 4.9 percent between 100 Hz and 20 Hz; and 4 percent between 40 Hz and 20 Hz. In this project, sampling frequency of 40 Hz was used.

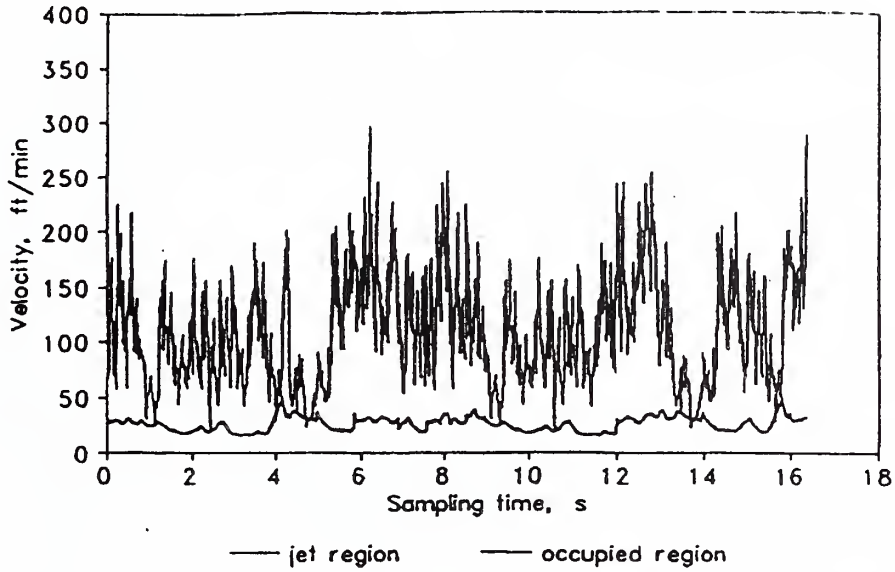


Figure 4.1.01. *Sample velocity signals: U_d = 350 fpm, T_{fd} = 0°F (jet region: x/w = 0.125, y/H = 0.0521; occupied region: x/w = 0.375, y/H = 0.6771). (Zhang, 1991)*

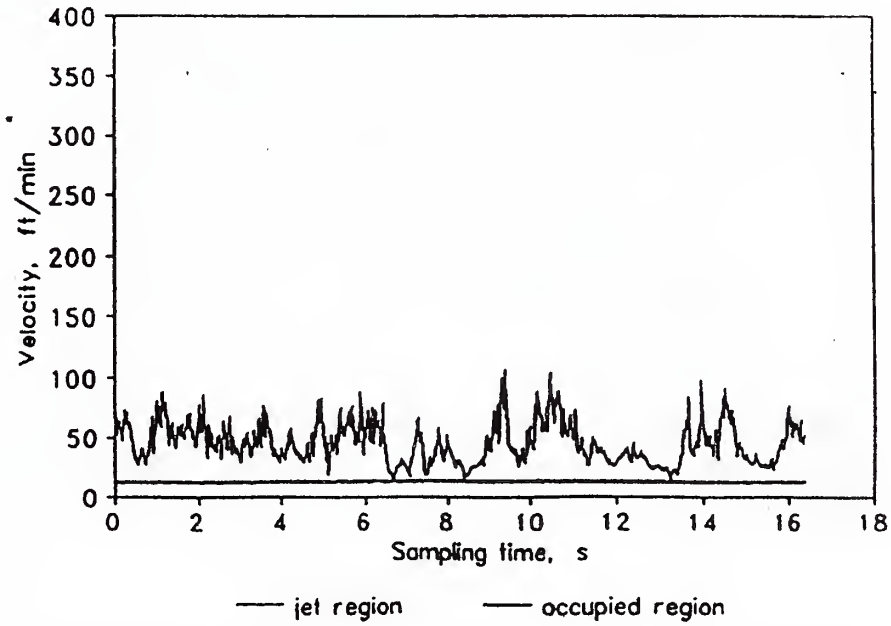


Figure 4.1.02. *Sample velocity signals: U_d = 150 fpm, T_{fd} = 0°F (jet region: x/w = 0.125, y/H = 0.0521; occupied region: x/w = 0.375, y/H = 0.6771). (Zhang, 1991)*

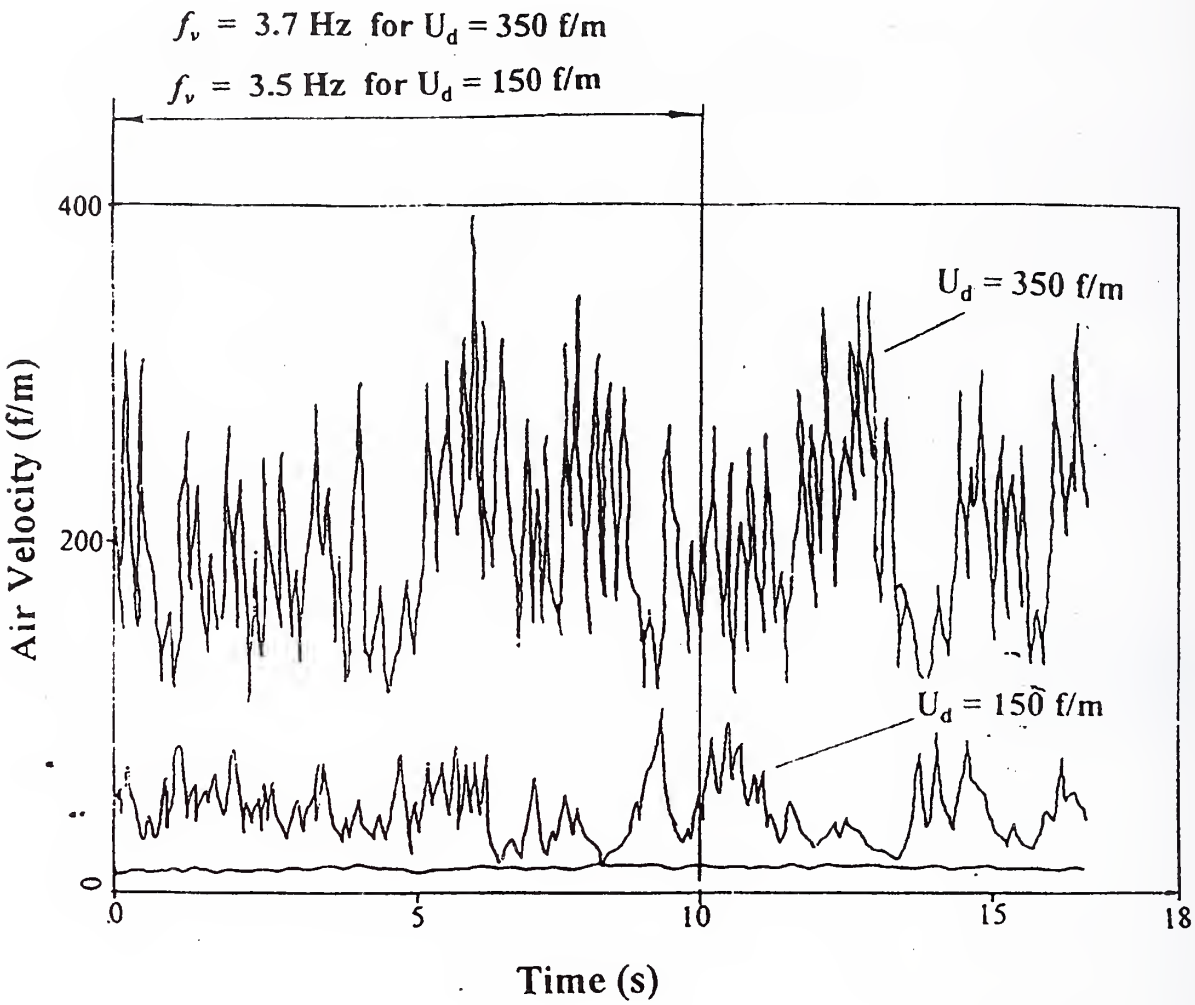


Figure 4.1.03. *Air velocity fluctuations in figures 4.1.01 and 4.1.02 through a low-pass filter. Secondary high frequency velocities were filtered out. Only primary flows with low frequencies are shown. Air velocity fluctuations in both primary flows (diffuser air velocity U_d = 350 fpm and 150 fpm) were less than 4 Hz.*

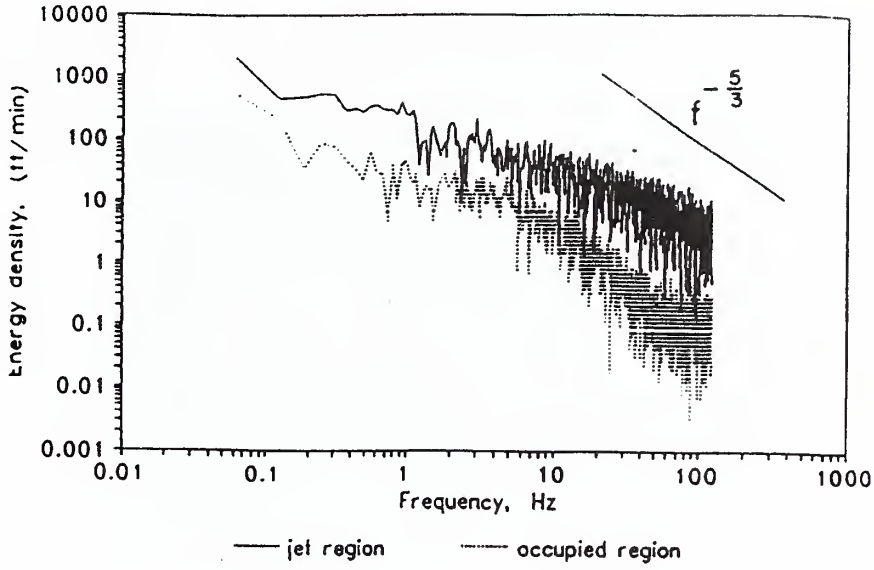


Figure 4.1.04. *Energy spectra or power spectra distribution (PSD) of air velocity: U_d = 500 fpm, T_{fd} = 0 °F (jet region: x/w = 0.125, y/H = 0.0521; occupied region: x/w = 0.375, y/H = 0.6771), (Zhang, 1991)*

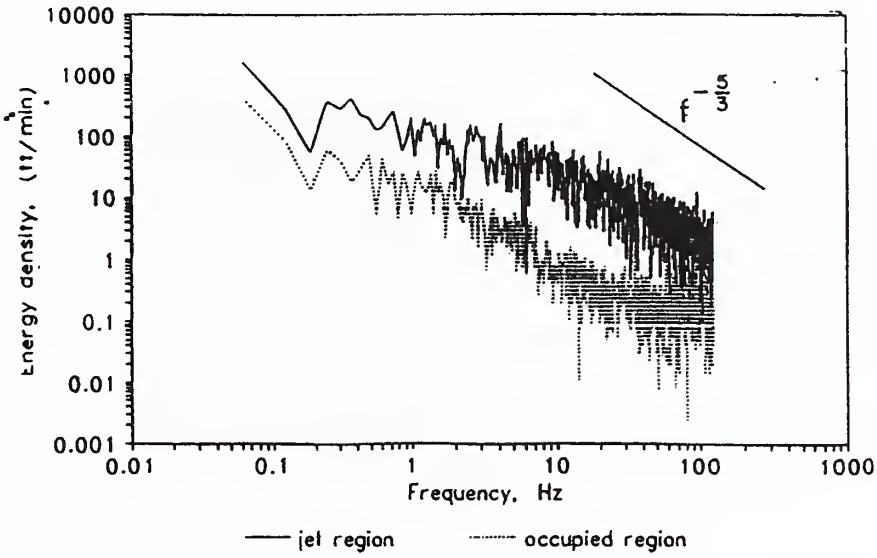


Figure 4.1.05. *Energy spectra or power spectra distribution (PSD) of air velocity: U_d = 350 fpm, T_{fd} = 0 °F (jet region: x/w = 0.125, y/H = 0.0521; occupied region: x/w = 0.375, y/H = 0.6771), (Zhang, 1991).*

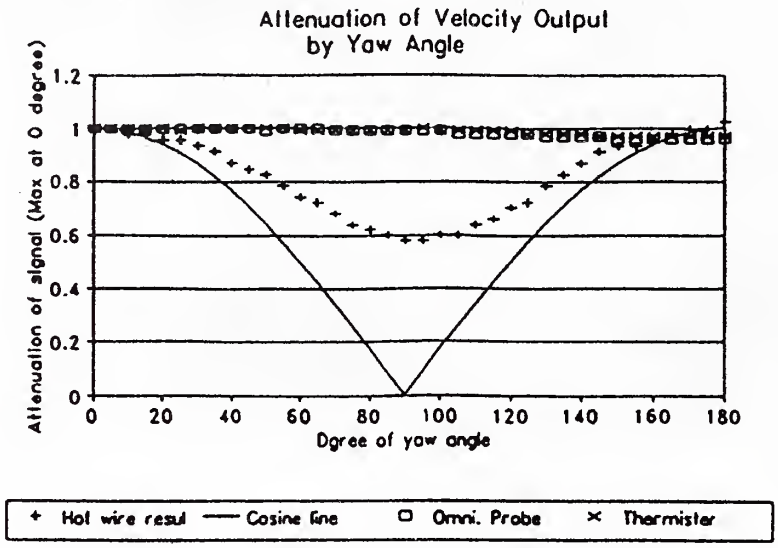


Figure 4.1.06. Directional responses of a hot wire anemometer and a thermistor anemometer. (Li, 1994)

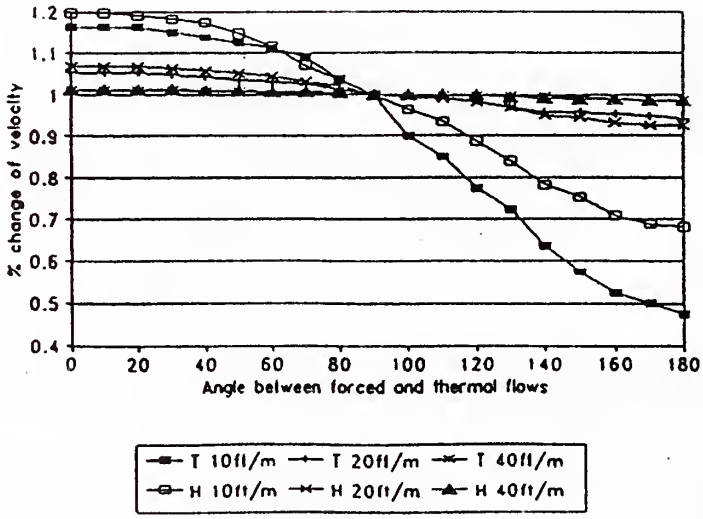


Figure 4.1.07. Comparison of self-heating errors between the hot wire and the BERL thermistor anemometers. (Li, 1994).

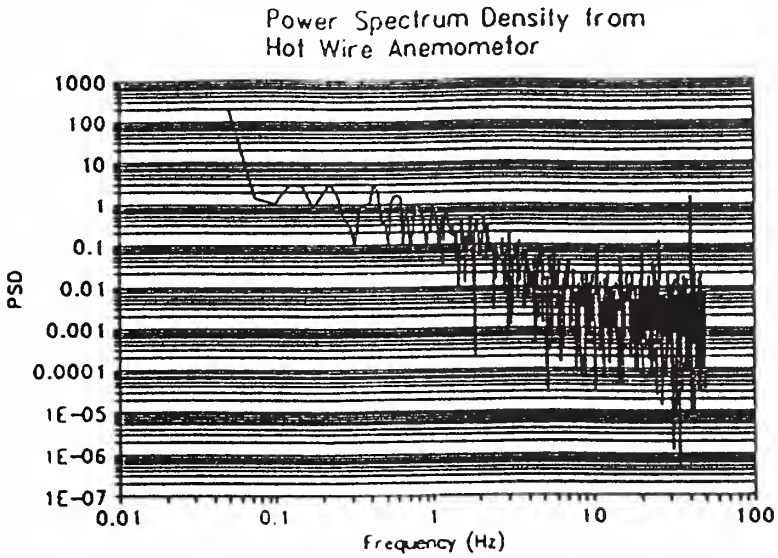


Figure 4.1.08. *Power spectra distribution from a TSI-IFA hot wire anemometer. (Li, 1994)*

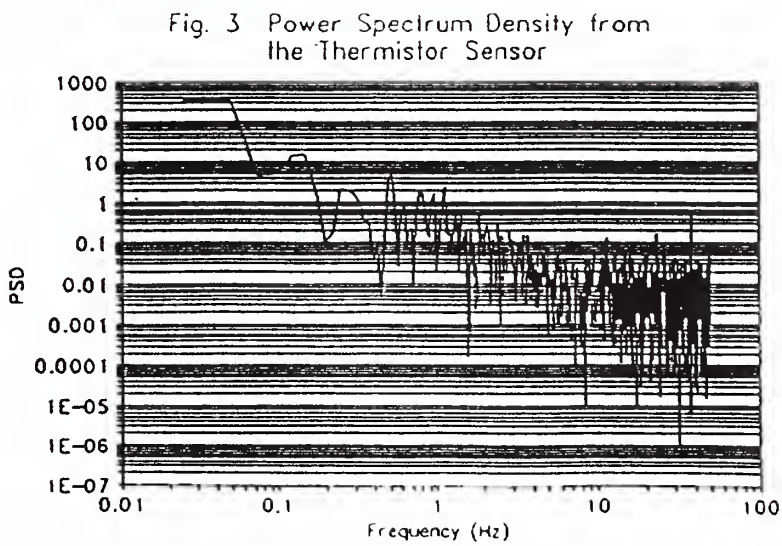


Figure 4.1.09. *Power spectra distribution from a BERL thermister anemometer. (Li, 1994)*

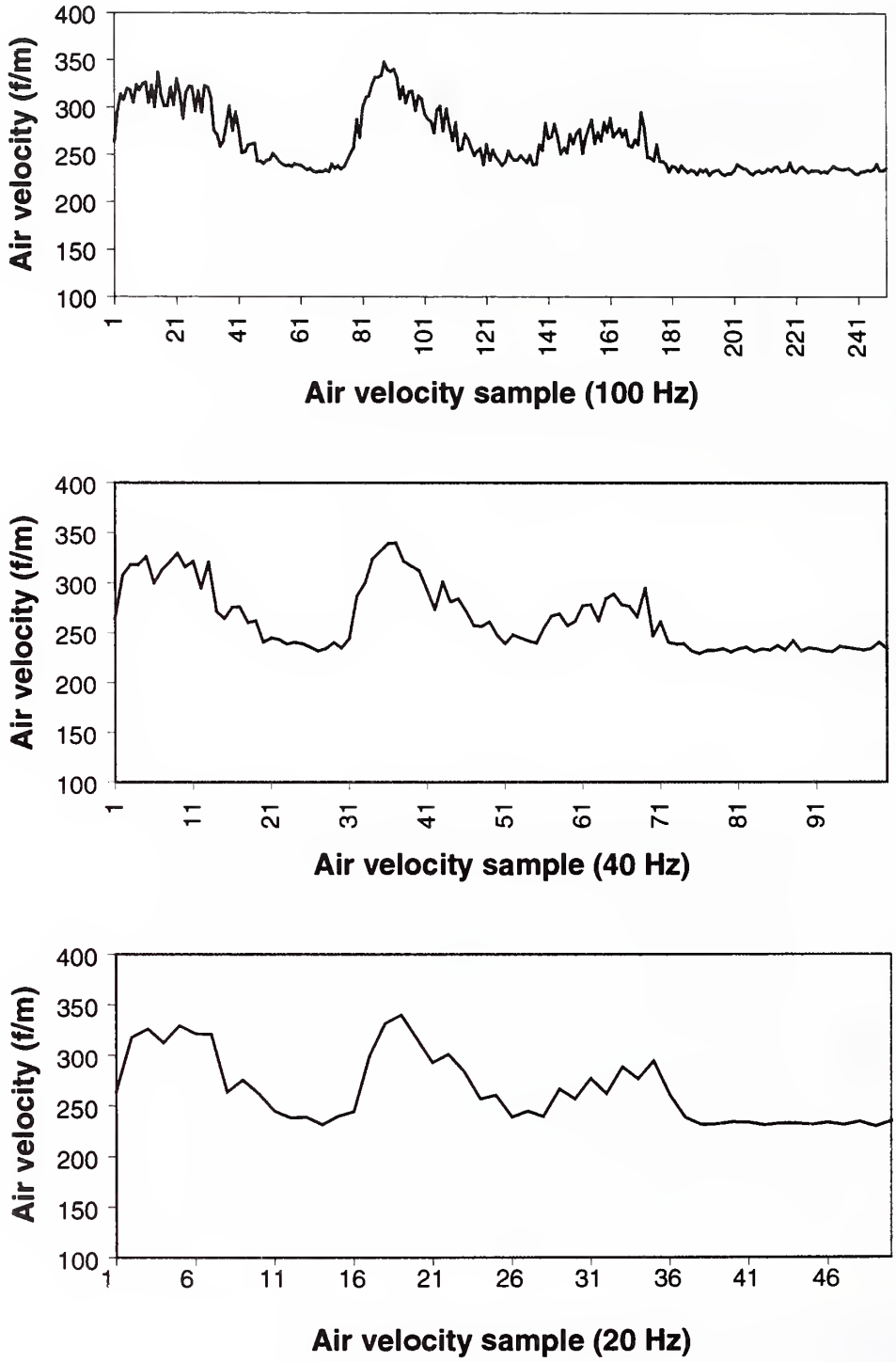


Figure 4.1.10. Comparison of air velocity fluctuations at different sampling frequencies. Upper: 100 Hz; Middle: 40 Hz; and Lower: 20 Hz.

4.2 Justification of Steady-State for Temperature and Air Velocity Field

4.2.1 Definition of Steady-State

In this project, steady-state is defined as when the fluctuation of mean air velocity and room temperature are less than 7 percent of the target value. The target value is the expected steady-state values over an extended period of time (in this case, mean values of over approximately two hours). For example, the target room temperature is 22.0 °C. Room temperatures within 22.0±1.5 °C (71.6±2.7 °F) (1.5 °C is 7 percent of 22.0 °C) is considered steady-state.

4.2.2 Justification

Air velocity responses:

Even at a very low air velocity, e.g., 0.05m/s (10 fpm), it only takes less than three minutes for a given air sample to travel from one location to any other location in the room and return. Thus, once the ventilation system is actuated and the door is closed, it is expected that a steady state-airflow field will be established within three minutes. To verify this assumption, air velocity fluctuations at one point (P_s) were measured. The point was near the end of traveling path of an air stream exiting from the exhaust: 0.61m (24") above floor, 0.61m (24") from west wall and 1.22m (48") from north wall. Figure 4.2.01 illustrates the air velocity fluctuations at this point 1, 4, 7, and 10 minutes after the door was closed, respectively.

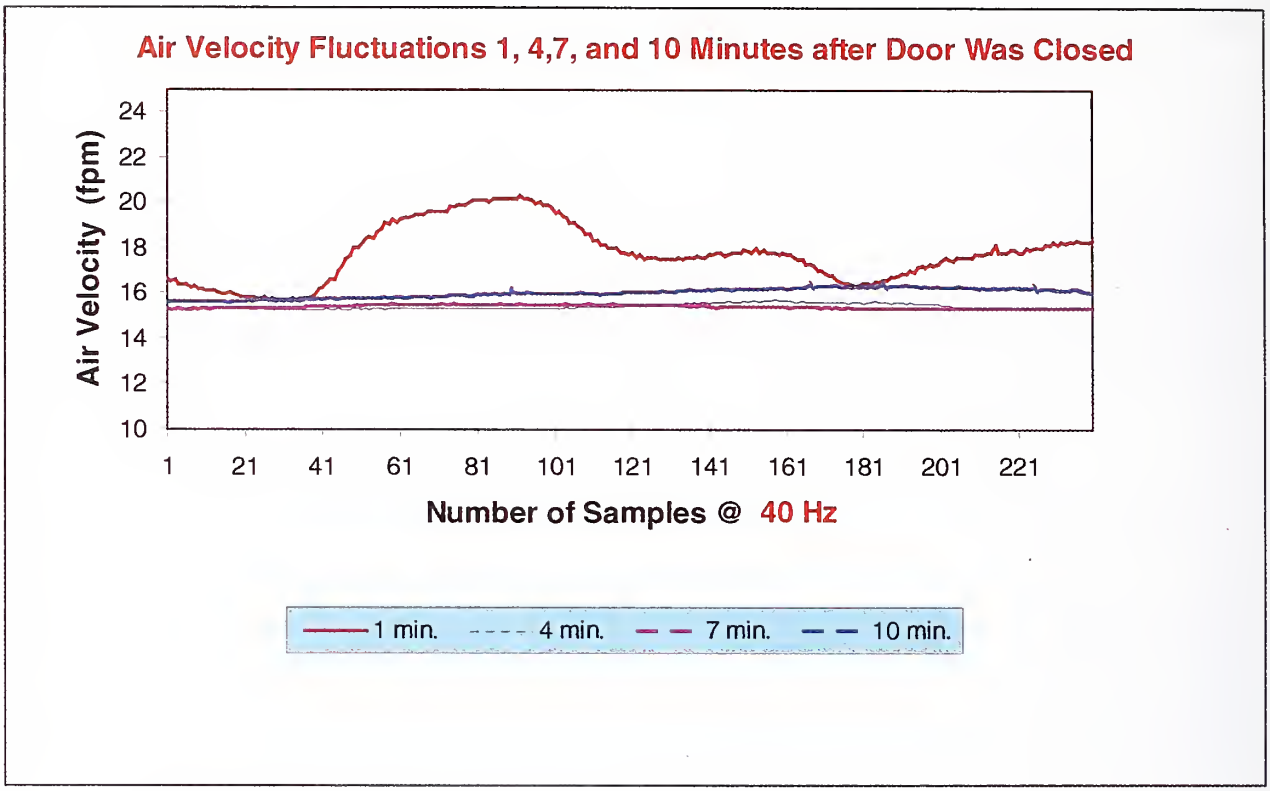


Figure 4.2.01. *Air velocity fluctuations 1, 4, 7, and 10 minutes after the door was closed, respectively*

The room air velocity field varied when the door closed for one minute. The mean air velocity became very consistent four minutes after the door was closed. The target air velocity at point P_s was 7.75e-2 m/s (15.5 fpm). The statistics for the mean air velocity are shown in table 4.2.01. The variation in mean air velocity was less than 1 percent after the door was closed for four minutes. Therefore, the airflow field was steady-state when the door was closed for four minutes and after.

Table 4.2.01. Variables measured after the door was closed for 1, 4, 7, and 10 minutes

	1 min	**4 min**	**7 min**	**10 min**	**Target**
U_{mean} (fpm)	17.77	15.41	15.39	15.99	15.50
SE for U_{mean} (fpm)	1.280	0.132	0.072	0.233	
TI (fpm)	0.072	0.0086	0.0047	0.0146	
U_{median} (fpm)	17.70	15.35	15.39	16.04	
Range of U_{mean} (fpm)	4.66	0.44	0.25	0.90	
Temperature (C)	22.89	22.99	22.88	23.01	22.78

Turbulence intensity

Because of the random nature of a turbulent flow in a room airspace (Zhang, 1991), the turbulence intensity can not be defined the same as the mean air velocity, i.e., turbulence intensity varies randomly as shown in table 4.2.01.

Room temperature

In general, steady-state for room temperature can take a few hours because of the large mass involved. However, the testing room is located within an air conditioned outer room in which the temperature is maintained at 22.0±1.5 °C (71.6±2.7 °F) regardless of the weather. Thus, the testing room is considered to be at a steady-state all the time. When the testing room door is opened, there may be a slight disturbance to the room temperature (usually a fraction of degree Celsius). Temperature response after the door was closed for 1, 4, 7, and 10 minutes are shown in table 4.2.01. The target room temperature was approximately 22.8 °C (73.0 °F). The testing room temperature elevation compared to the outer room temperature (22.0 °C) was due to the heating load of step motors and thermisters in the testing room. Temperatures in the testing room varied less than 1 percent of the target temperature for all four measurement periods. Therefore, the room temperature was in steady state after the door was closed for one minute.

4.2.3 Conclusion

A steady state both for velocity and temperature in the testing room can be achieved after the door was closed for 4 minutes. Data collection in this project was started 10 minutes after the door was closed to ensure steady state.

4.3 Empty Room Data

4.3.1 Surface Temperature and Ventilation System Data

Data Files	Z1up-e8 to Z1up-e12	Z1up-e1 to Z1up-e7	Z1up-m8 to Z1up-m15	Z1up-m4 to Z1up-m7	Z1up-m1 to Z1up-m3	Z1up-w1 to Z1up-w7	Z1up-w8 to Z1up-w15
Room Surface Temp (F)							
Walls:							
South (Center)	68	68	71	70	69	70	70
West (Center)	70	69	69	70	68	70	70
North (East of Door)	71	70	69	69	69	70	70
North (West of Door)	70	69	69	70	69	70	70
East (Center)	70	69	68	70	68	70	70
Floor (Center)	69	69	65	68	68	69	69
Ceiling:							
South	68	68	69	69	68	70	70
West	70	69	70	70	68	70	70
North	70	70	70	70	69	70	71
East	70	69	70	68	69	70	70
Room Airflow (cfm)							
Supply Fan	128	128	128	128	128	129	128
Exhaust Fan	102	102	105	103	103	104	103
Pressure Difference (in. water)	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Barometric Pressure (mm Hg)	29.13	29.03	29.16	29.13	29.28	29.38	29.35

Data Files	Z1lw-w8 to Z1lw-w15	Z1lw-w1 to Z1lw-w7	Z1lw-m8 to Z1lw-m15	Z1lw-m1 to Z1lw-m7	Z1lw-e1 to Z1lw-e15	Z2se-1 to Z2se-7	Z2sw-1 to Z2sw-7
Room Surface Temp (F)							
Walls:							
South (Center)	70	71	70	71	70	72	70
West (Center)	71	72	70	71	71	72	70
North (East of Door)	70	72	71	71	71	72	70
North (West of Door)	70	72	71	71	71	72	70
East (Center)	70	72	70	71	71	72	70
Floor (Center)	70	71	70	71	70	70	68
Ceiling:							
South	70	72	70	70	71	71	69
West	70	72	70	71	71	72	70
North	71	72	71	71	71	72	70
East	71	72	71	71	71	72	69
Room Airflow (cfm)							
Supply Fan	128	128	128	128	127	127	130
Exhaust Fan	99	101	102	102	100	100	101
Pressure Difference (in. water)	0.04	0.04	0.04	0.04	0.04	0.02	0.03
Barometric Pressure (mm Hg)	29.18	29.17	29.05	29.03	29.15	29.15	29.39

Data Files	Z2nw-1 to Z2nw-7	Z2ne-1 to Z2ne-7	Z2nm-1 to Z2nm-13	Z3ex-n15 to n16; s1 to s4	Z3ex-n1 to Z3ex-n14	Z3ex-s5 to Z3ex-s7	Z3ex-s8
Room Surface Temp (F)							
Walls:							
South (Center)	71	70	69	70	68	68	69
West (Center)	71	70	69	70	69	69	69
North (East of Door)	71	71	69	70	68	68	69
North (West of Door)	70	70	68	70	68	69	69
East (Center)	71	71	69	70	69	68	69
Floor (Center)	70	70	68	69	68	68	67
Ceiling:							
South	71	70	69	70	70	68	70
West	72	70	70	71	70	69	69
North	71	71	70	71	70	69	70
East	71	71	70	70	70	70	70
Room Airflow (cfm)							
Supply Fan	129	129	130	129	129	129	128
Exhaust Fan	96	103	98	103	103	102	102
Pressure Difference (in. water)	0.05	0.04	0.06	0.04	0.04	0.04	0.04
Barometric Pressure (mm Hg)	29.59	28.87	29.47	29.06	29.06	29.05	29.1

4.3.2 Zone 1

Zone 1 (the room airspace) was divided into three sections: East (E), Middle (M) and West (W) (figure 4.3.01). Each section was divided into two parts: upper (UP) and lower (LW). Upper part (30" above floor to ceiling, data point distances: 30, 36, 42, and 90" from floor) contains 11 vertical points, and lower part (from floor to 24" above the floor, data point distances: 6, 12, 18, and 24" above floor) contains 4 vertical points. Data were collected six inches from walls, ceiling and floor, and at six inch intervals within the room airspace.

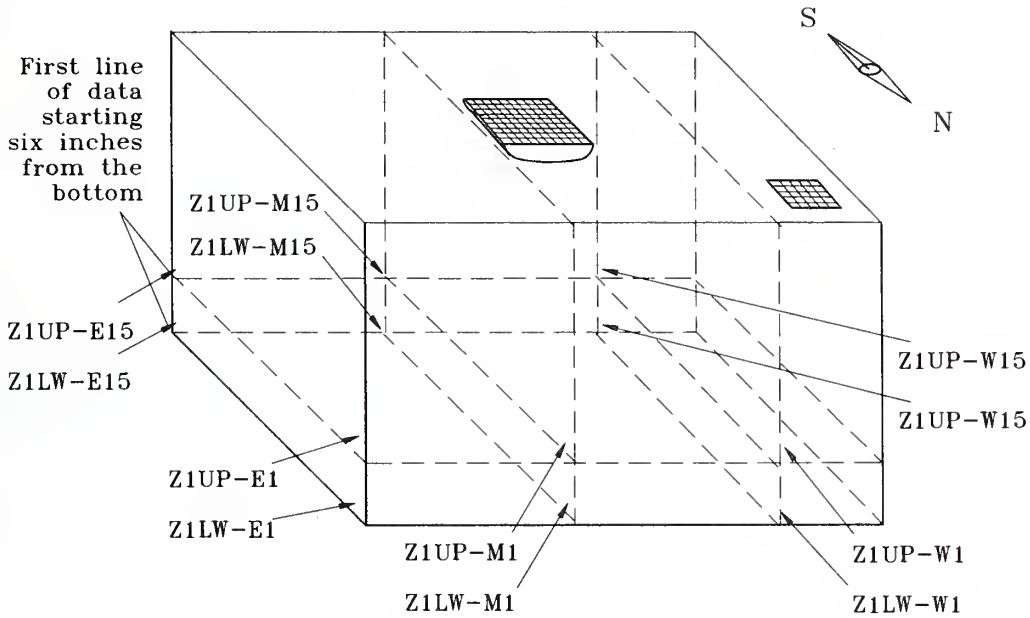
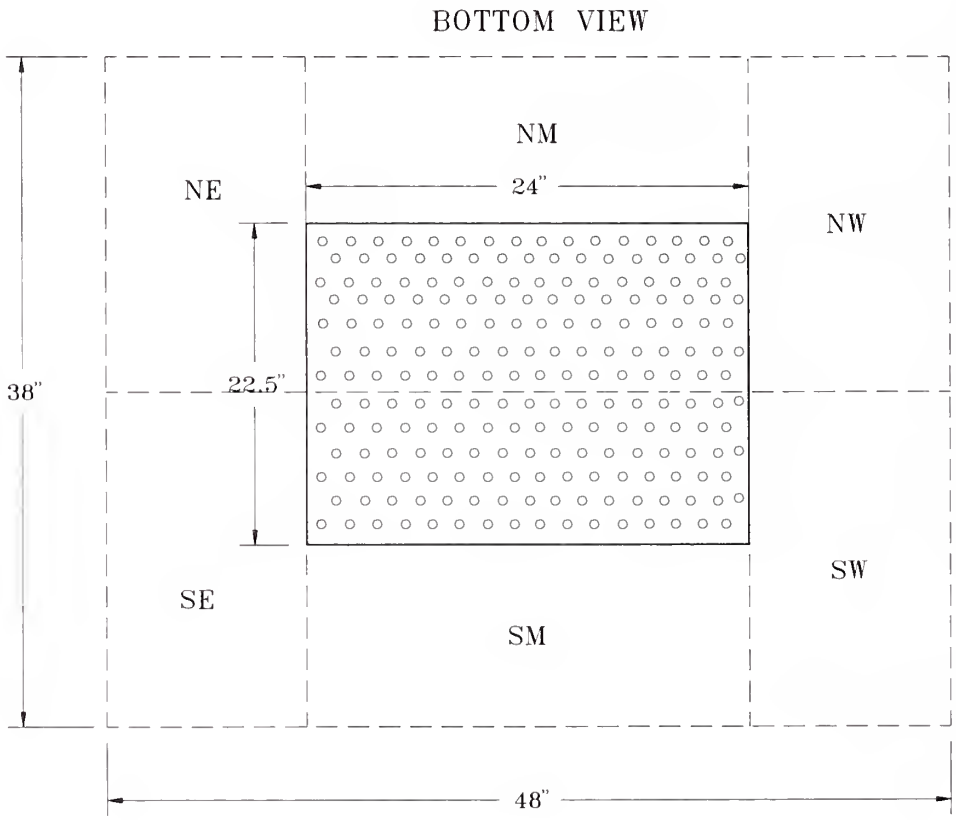


Figure 4.3.01. *Data file location in Zone 1. Arrows point at the first data in the file.*

4.3.3 Zone 2

Zone 2 was divided into six sections: north-east (NE), north-middle (NM), north-west (NW), south-east (SE), south-middle (SM), and south-west (SW) (figure 4.3.02). The number (figure 4.3.02: Lower) in the filename starts from the far east location. Lowest points were 12" from the ceiling for NE, NW, SE and SW sections. For NM and SM sections, lowest points were 16" below the ceiling due to the projection of the diffuser discharge surface. Data were collected two inches from the ceiling, and at 2" intervals within Zone 2.



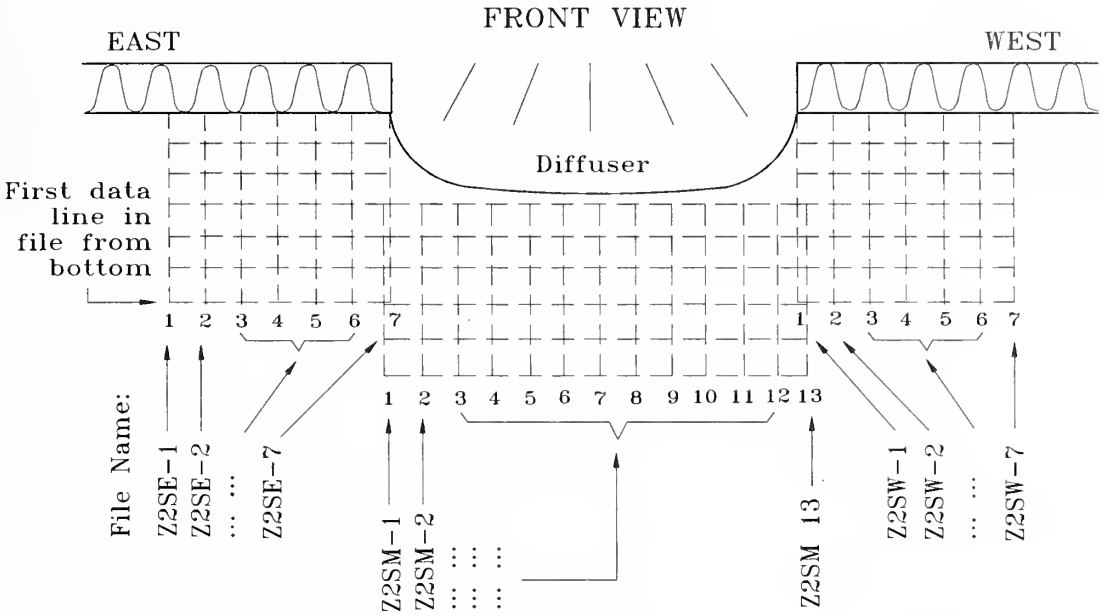


Figure 4.3.02. *Data file location in Zone 2. Upper: Bottom view of sections used for data collection, e.g., NW = north west. Lower: Front view from north.*

4.3.4 Zone 3

Zone 3 was divided into 2 sections: south (S) and north (N). Number in a data file starts from the east side of zone 3 and indicates the distance from the east side of the zone. Lowest points (first row of data) were 12" below the ceiling. Data were collected 2" from the ceiling, and at 2" intervals within Zone 3.

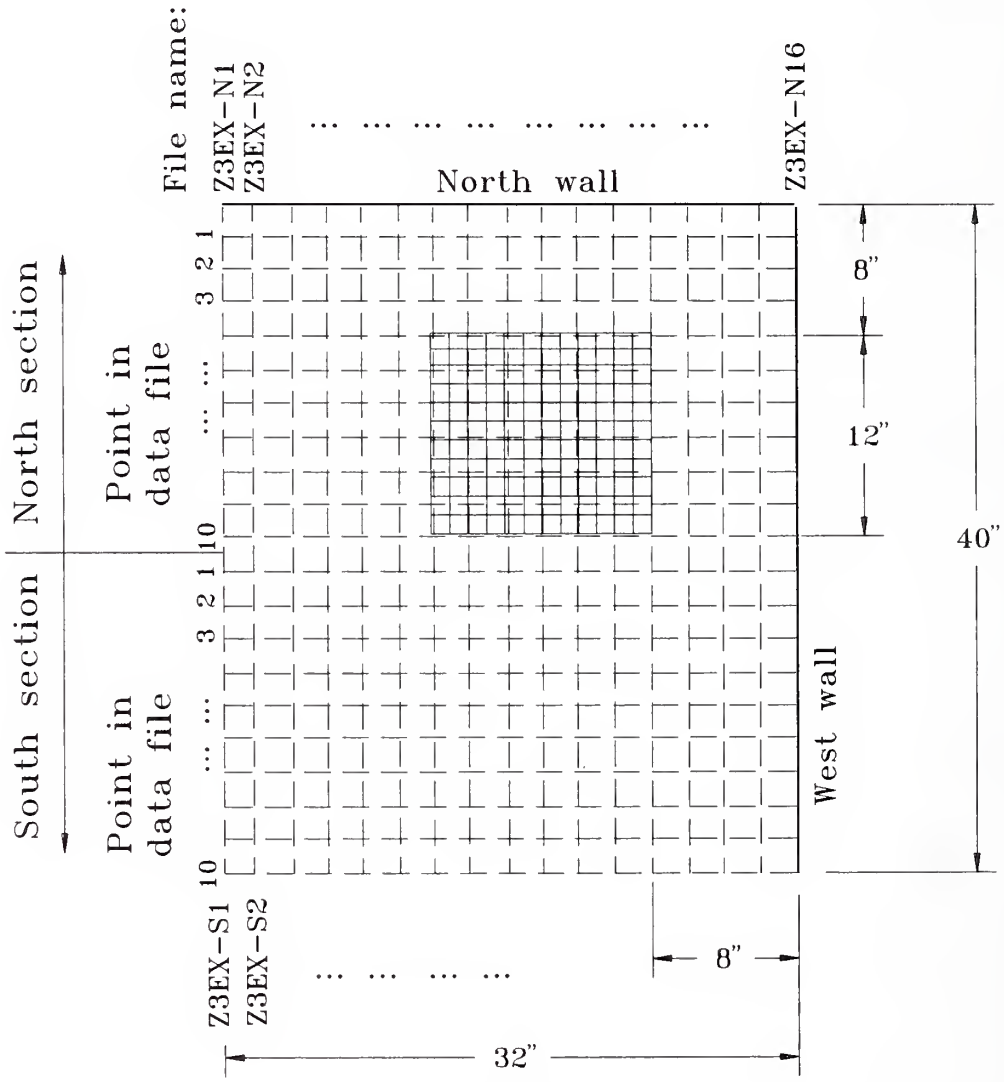


Figure 4.3.03. A bottom view of Zone 3 and data file locations

4.4 Populated Room Data

4.4.1 General Details

The overview of the measurement zones are shown in figure 4.4.01, the starting locations of the measurement zones are shown in figure 4.4.02, and the start and end measuring points are tabulated in table 4.4.01.

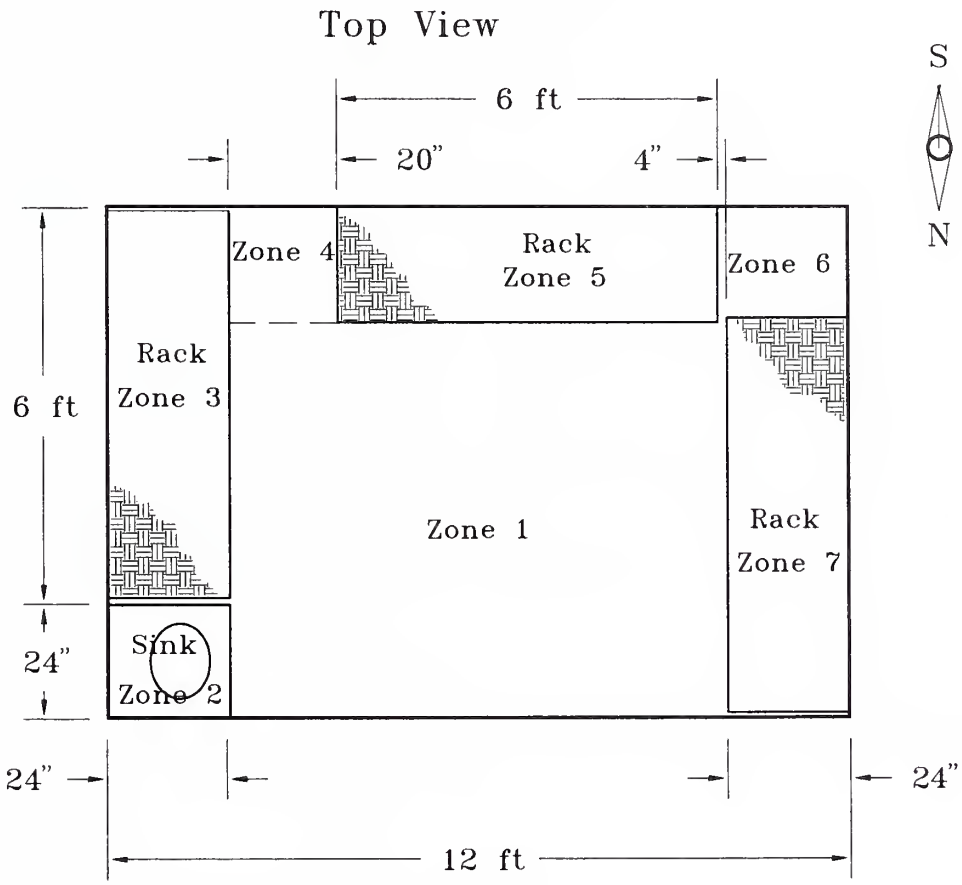


Figure 4.4.01. *Top view of zones in the room: three racks are identical, each rack has six shelves and each shelf supports seven mouse cages.*

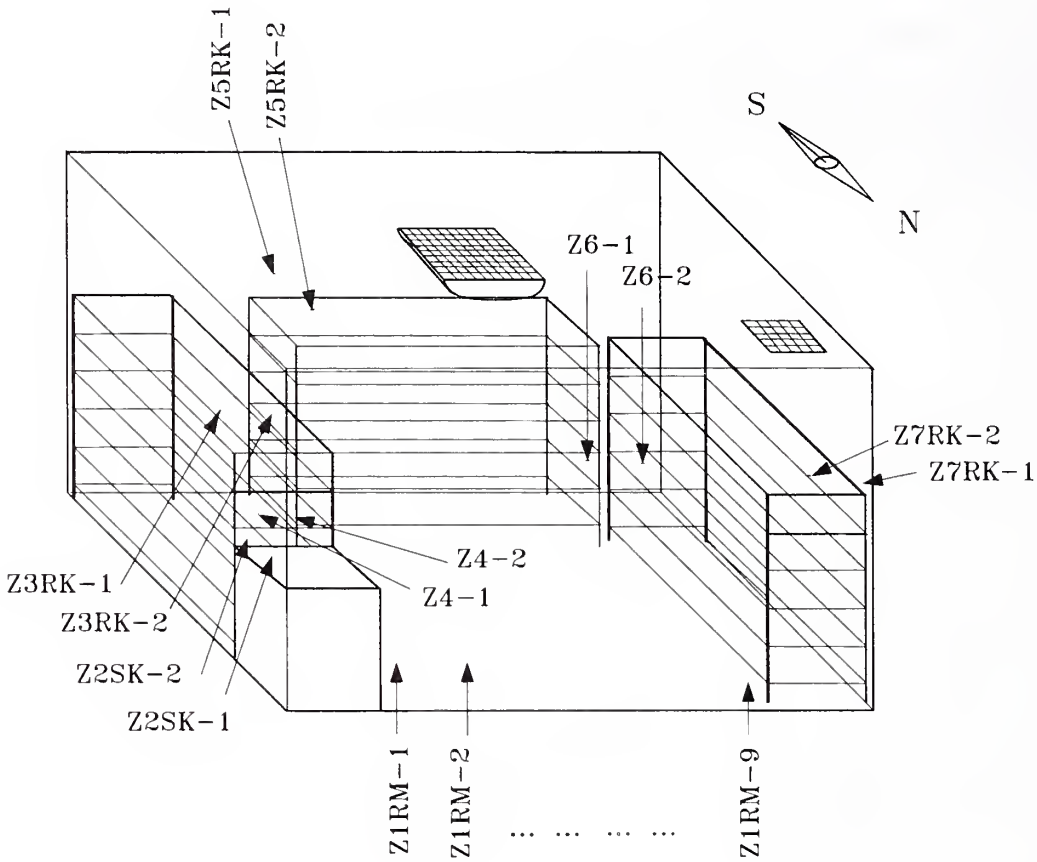


Figure 4.4.02. Illustration of data point locations in each zone

Table 4.4.01 Data Locations for Populated Room

Zone	File	Location of First Data Point	Location of Last Data Point
1	Z1RM-1	2" to N wall, 26" to E wall, 12" to floor	2" to N wall, 26" to E wall, 12" to ceil.
	Z1RM-2	2" to N wall, 38" to E wall, 12" to floor	2" to N wall, 38" to E wall, 12" to ceil.
	Z1RM-3	2" to N wall, 50" to E wall, 12" to floor	2" to N wall, 50" to E wall, 12" to ceil.
	Z1RM-4	2" to N wall, 62" to E wall, 12" to floor	2" to N wall, 62" to E wall, 12" to ceil.
	Z1RM-5	2" to N wall, 74" to E wall, 12" to floor	2" to N wall, 74" to E wall, 12" to ceil.
	Z1RM-6	2" to N wall, 86" to E wall, 12" to floor	2" to N wall, 86" to E wall, 12" to ceil.
	Z1RM-7	2" to N wall, 98" to E wall, 12" to floor	2" to N wall, 98" to E wall, 12" to ceil.
	Z1RM-8	2" to N wall, 110" to E wall, 12" to floor	2" to N wall, 110" to E wall, 12" to ceil.
	Z1RM-9	2" to N wall, 122" to E wall, 12" to floor	2" to N wall, 122" to E wall, 12" to ceil.
2	Not Measured		
3	Z3RK-1	2" to N wall, 14" to E wall, 24" to ceil.	2" to N wall, 14" to E wall, 12" to ceil.
	Z3RK-2	2" to N wall, 2" to E wall, 24" to ceil.	2" to N wall, 2" to E wall, 12" to ceil.
4	Not Measured		
5	Z5RK-1	2" to S wall, 2" to E wall, 24" to ceiling	2" to S wall, 2" to E wall, 12" to ceiling
	Z5RK-2	2" to S wall, 14" to E wall, 24" to ceiling	2" to S wall, 14" to E wall, 12" to ceiling
	Z5RK-3	2" to S wall, 26" to E wall, 24" to ceiling	2" to S wall, 26" to E wall, 12" to ceiling
	Z5RK-4	2" to S wall, 38" to E wall, 24" to ceiling	2" to S wall, 38" to E wall, 12" to ceiling
	Z5RK-5	2" to S wall, 50" to E wall, 24" to ceiling	2" to S wall, 50" to E wall, 12" to ceiling
	Z5RK-6	2" to S wall, 62" to E wall, 24" to ceiling	2" to S wall, 62" to E wall, 12" to ceiling
	Z5RK-7	2" to S wall, 74" to E wall, 24" to ceiling	2" to S wall, 74" to E wall, 12" to ceiling
	Z5RK-8	2" to S wall, 86" to E wall, 24" to ceiling	2" to S wall, 86" to E wall, 12" to ceiling
	Z5RK-9	2" to S wall, 98" to E wall, 24" to ceiling	2" to S wall, 98" to E wall, 12" to ceiling
	Z5RK-10	2" to S wall, 110" to E wall, 24" to ceiling	2" to S wall, 110" to E wall, 12" to ceiling
	Z5RK-11	2" to S wall, 122" to E wall, 24" to ceiling	2" to S wall, 122" to E wall, 12" to ceiling
	Z5RK-12	2" to S wall, 134" to E wall, 24" to ceiling	2" to S wall, 134" to E wall, 12" to ceiling
	Z5RK-13	2" to S wall, 144" to E wall, 24" to ceiling	2" to S wall, 144" to E wall, 12" to ceiling
6	Not Measured		
7	Z7RK-1	2" to N wall, 2" to W wall, 24" to ceil.	2" to N wall, 2" to W wall, 12" to ceil.
	Z7RK-2	2" to N wall, 14" to W wall, 24" to ceil.	2" to N wall, 14" to W wall, 12" to ceil.

5. PHOTOGRAPHS FROM EXPERIMENTAL TESTS

Presented below are a series of plates taken during the experimental phases of the project.

5.1 Cage Condition

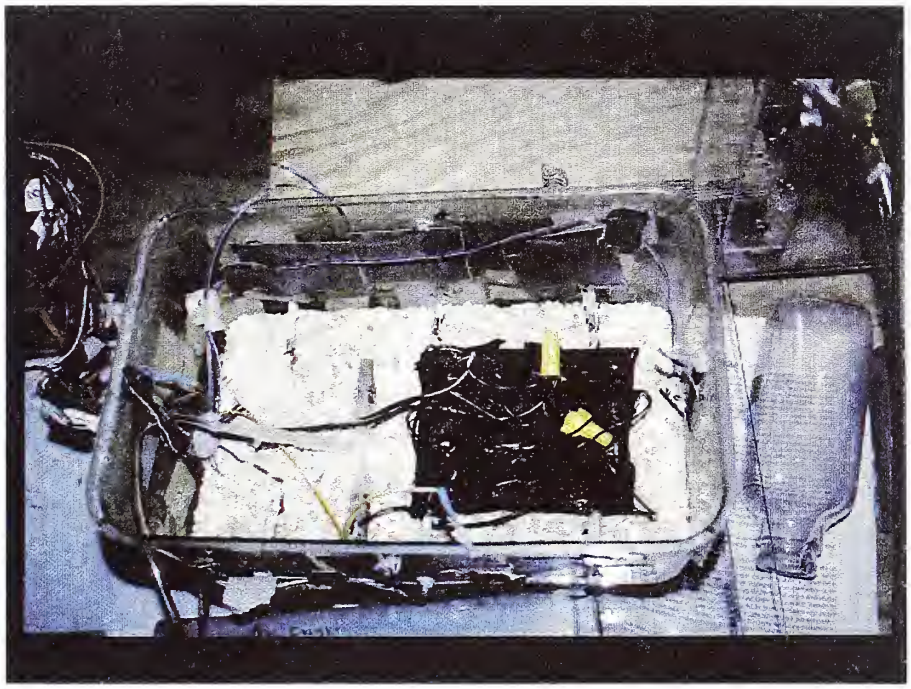


Figure 5.1.01 *Simulated Mice Obstruction (SMO)*

Figure 5.1.02 *Default Mice Heater (DMH)*

Figure 5.1.03 *Sealed Lip Microisolator*

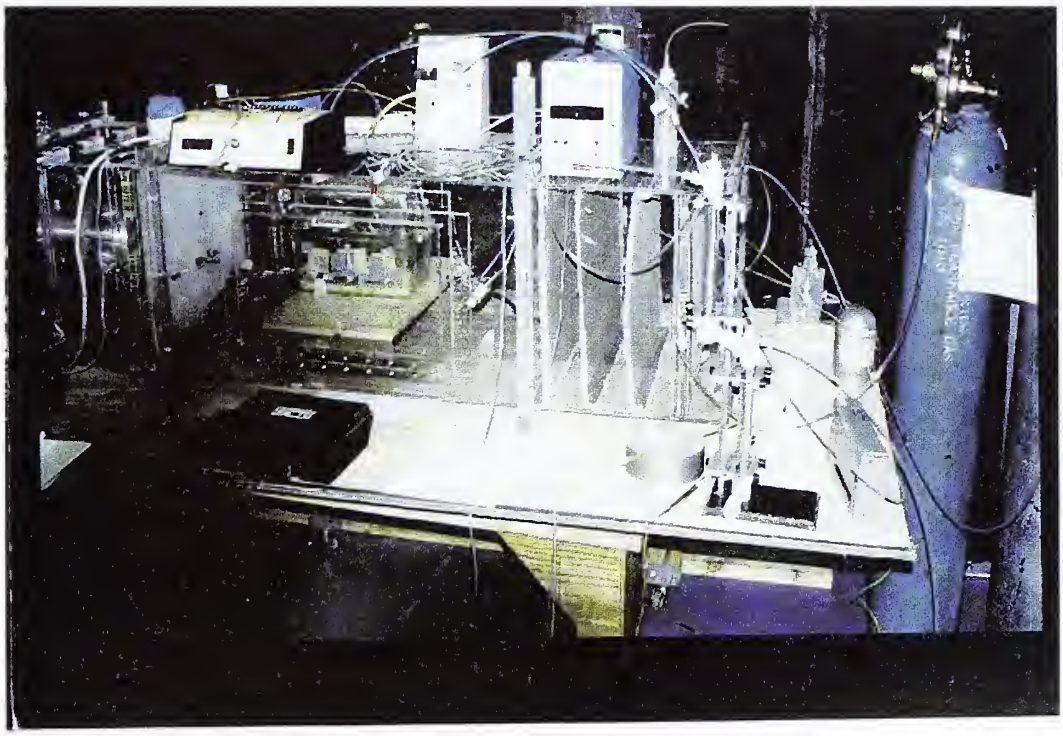


Figure 5.1.04 *Wind Tunnel in Parallel Cage Orientation*

Figure 5.1.05 *Microisolator Cage with Sampling Tube*

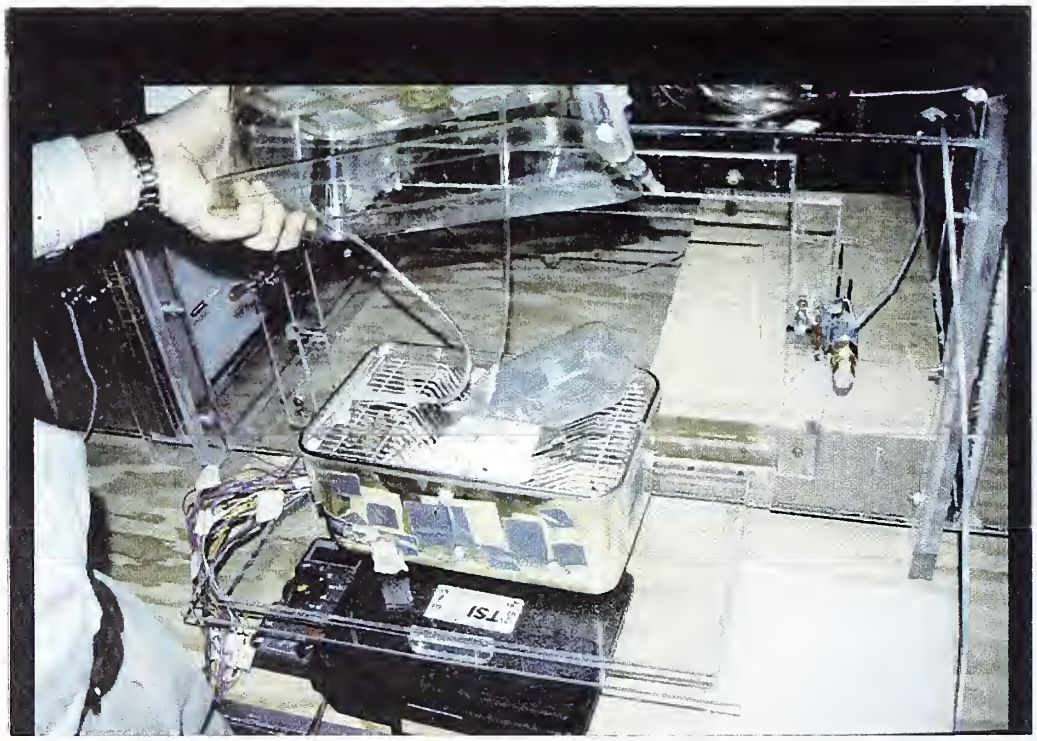


Figure 5.1.06 *Microisolator Showing Internal Sampling Tubes*

Figure 5.1.07 *Microisolator Cage Used in Wind Tunnel*

Figure 5.1.08 *Tedlar, Polyvinyl Fluoride – CO2 Gas Sampling Bags*

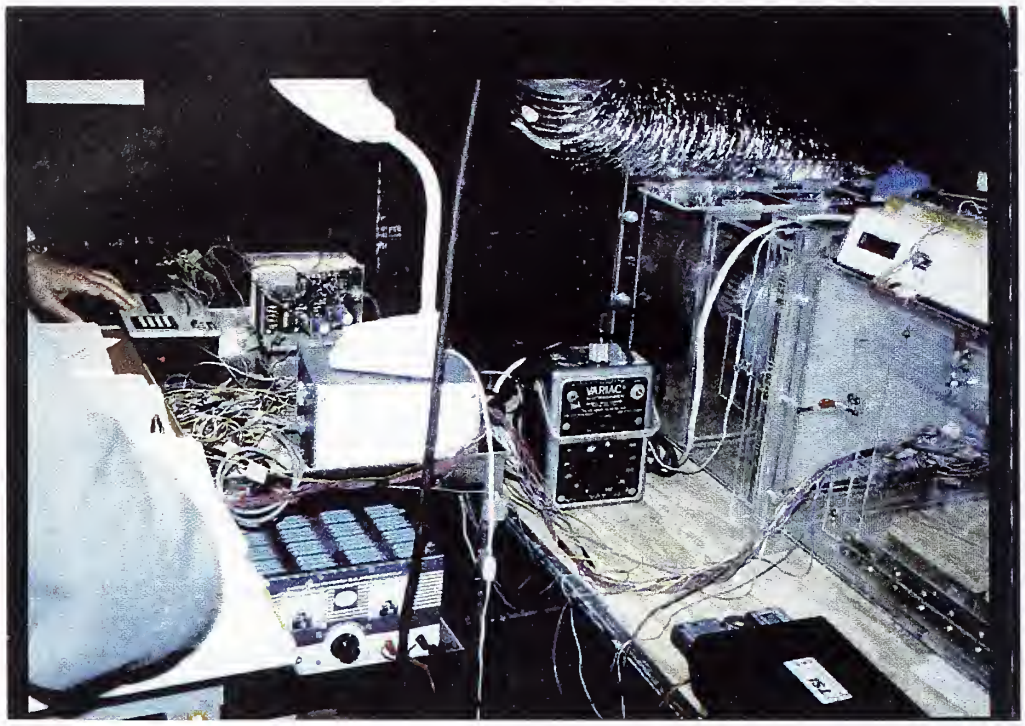


Figure 5.1.09 *Wind Tunnel Data Logger and Airflow Controller*

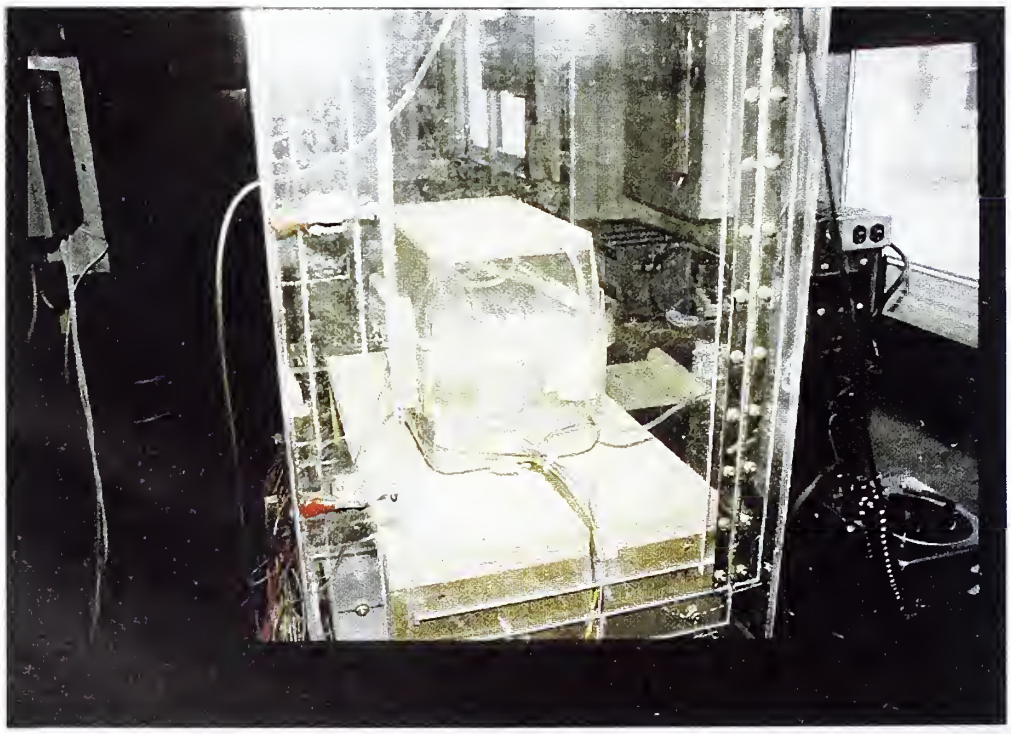


Figure 5.1.10 *Vertically Orientated Wind Tunnel*

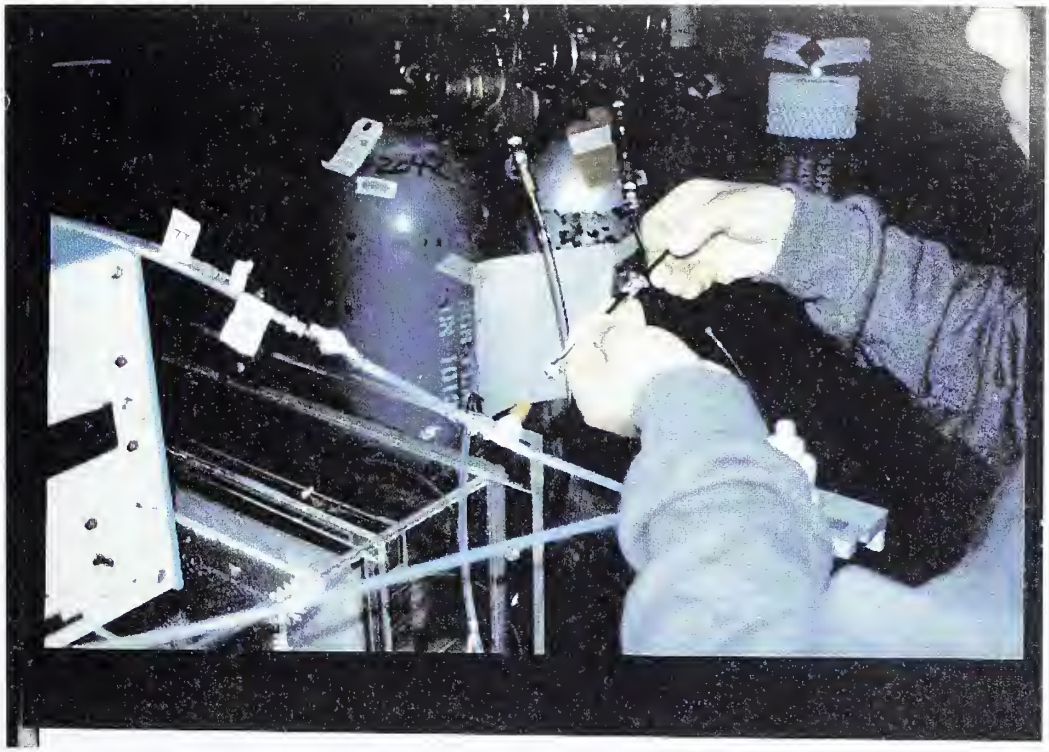


Figure 5.1.11 *Drawing Gas Samples Using Gas Chromatography*

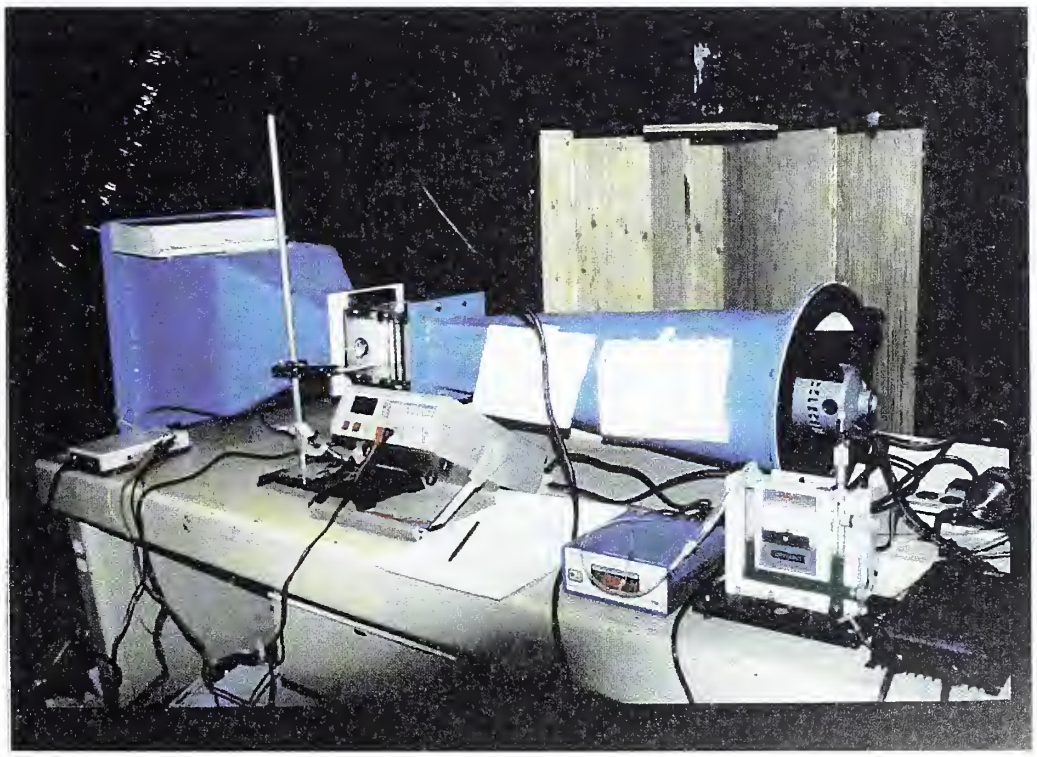


Figure 5.1.12 *Velocity Calibration Device*

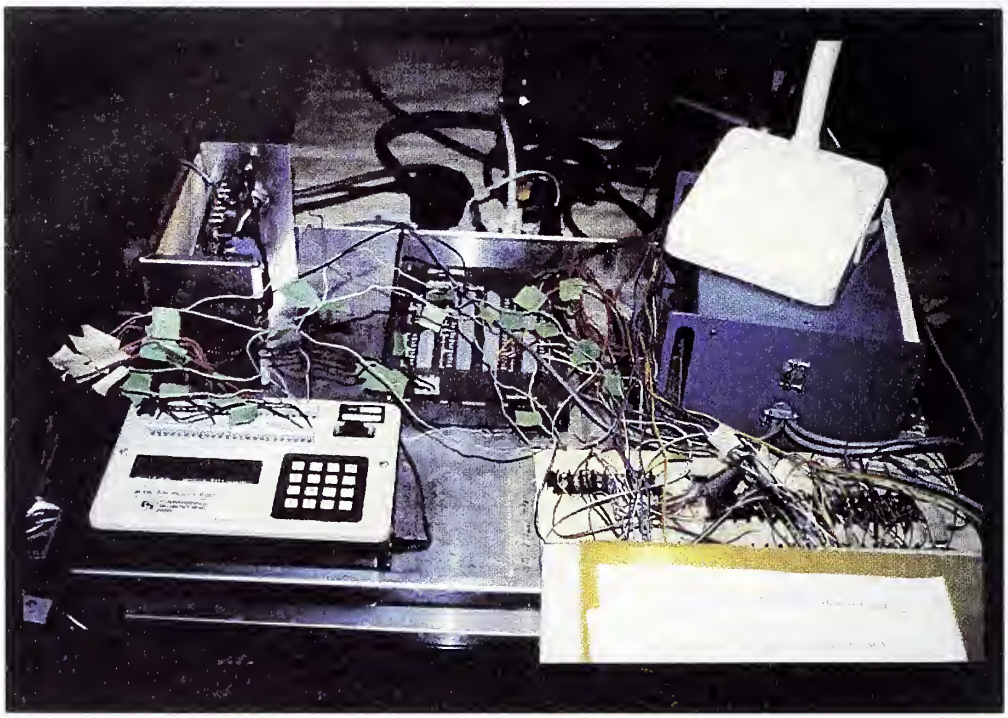


Figure 5.1.13 *Data Logger for Temperature and Velocity*

Figure 5.1.14 *Microisolator Outside Sampling Tube*

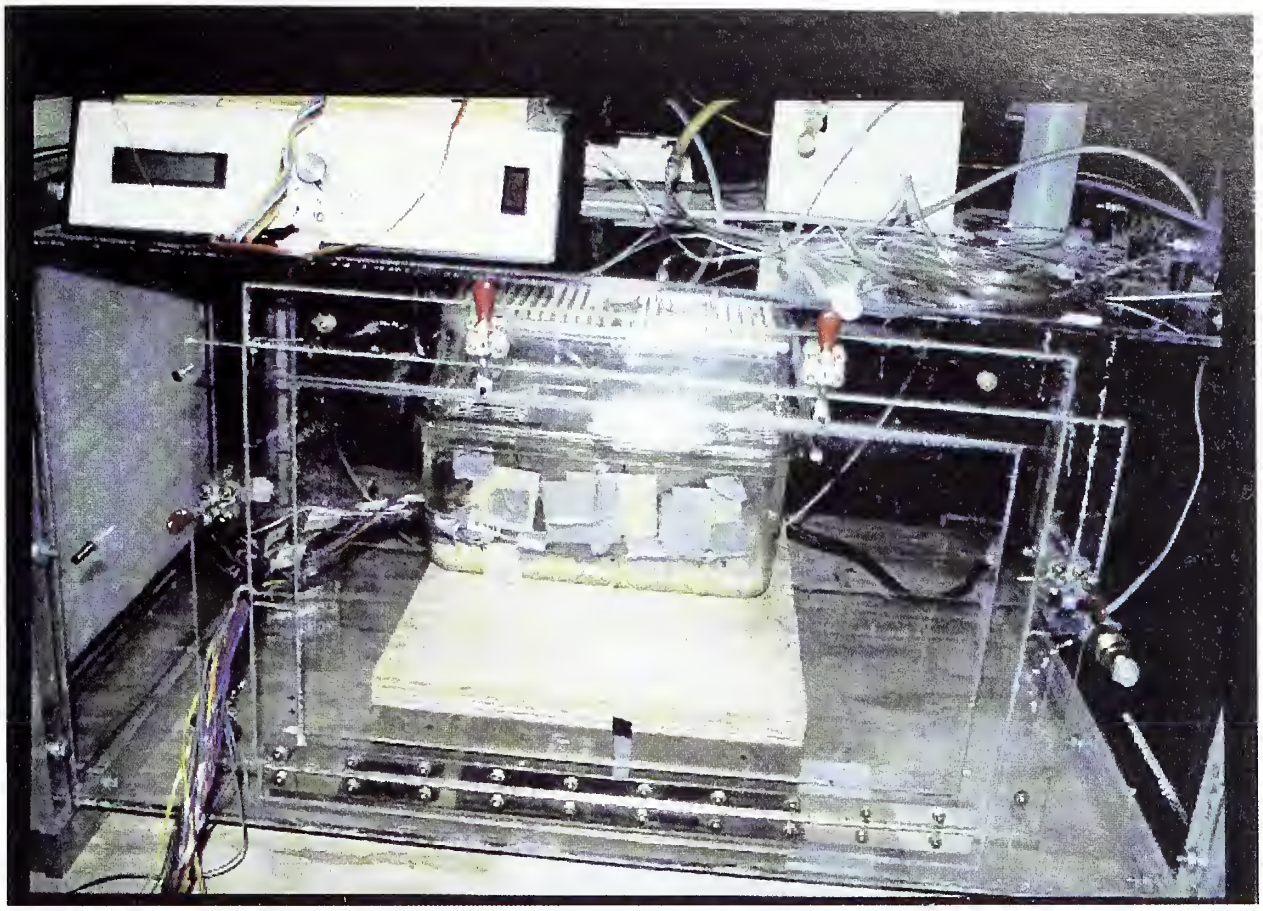


Figure 5.1.15 *Microisolator Cage in Wind Tunnel: Parallel Cage Orientation*

5.2 CO2, NH3, H2O and Heat Generation Measurements at Low and High Humidities

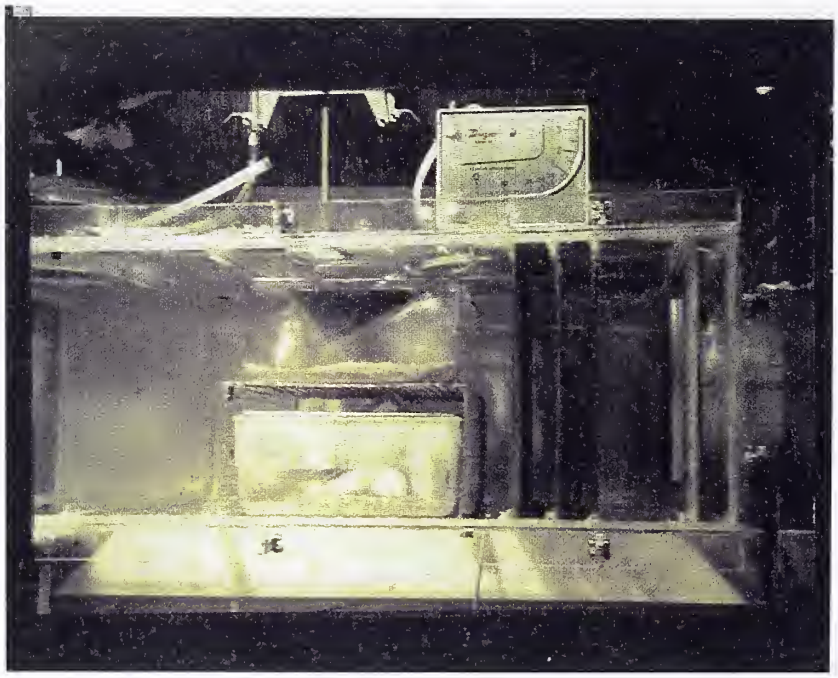


Figure 5.2.01 *An Indirect Convective Calorimeter*

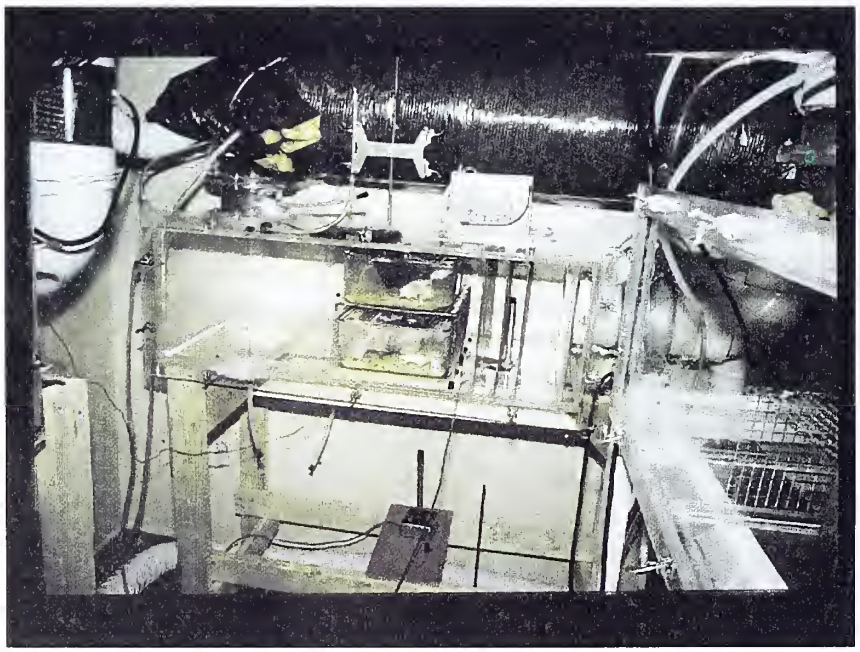


Figure 5.2.02 *An Indirect Convective Calorimeter #2*

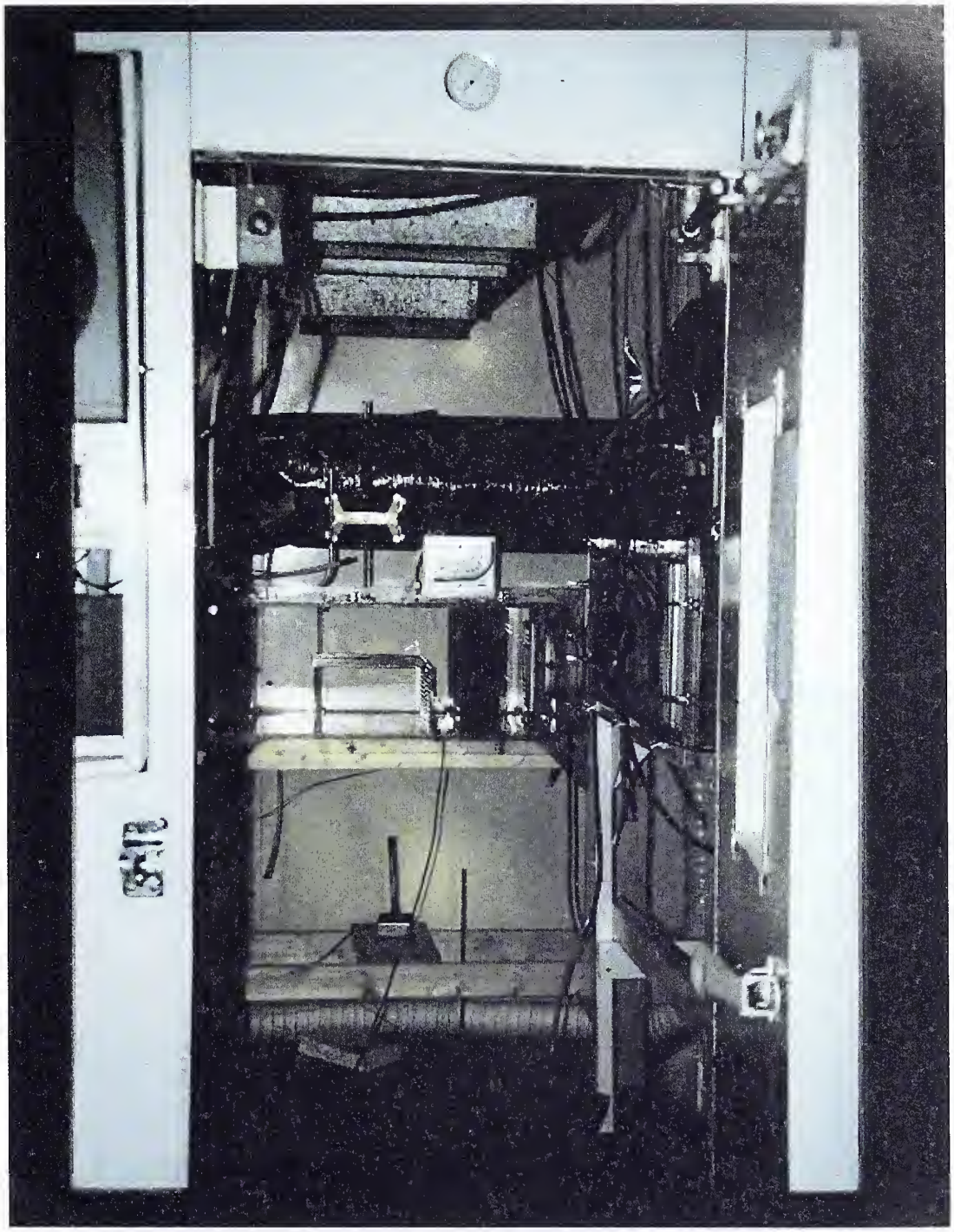


Figure 5.2.03 *An Indirect Calorimeter #3*

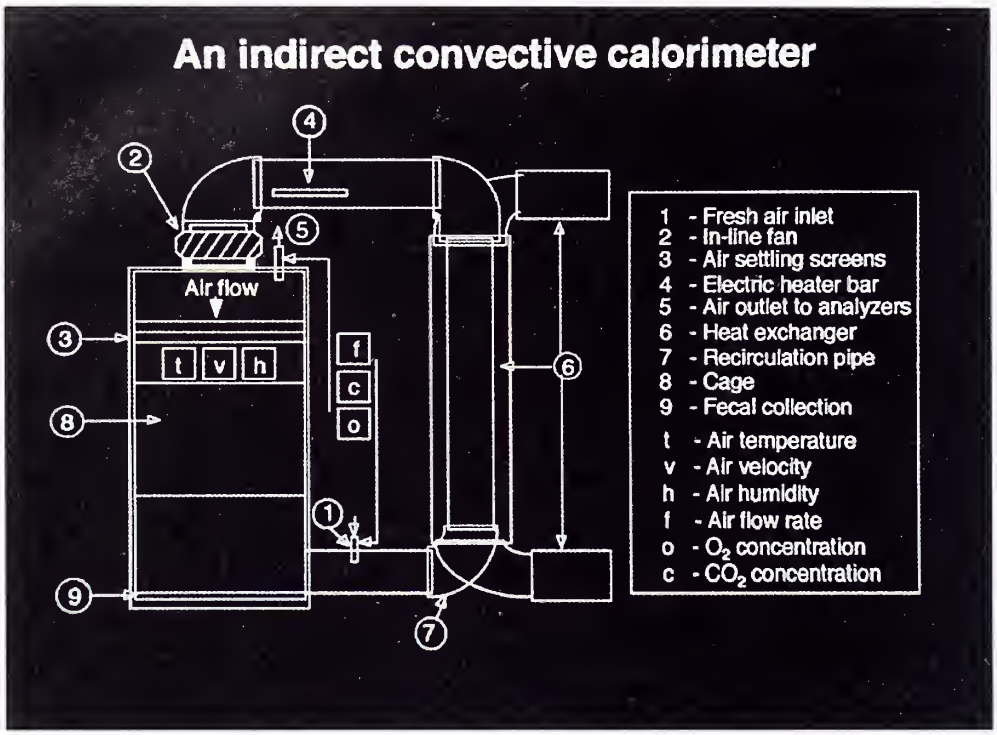


Figure 5.2.04 *Flow Diagram - Indirect Convective Calorimeter*

Figure 5.2.05 *Outbred Mice: Female – HSD – ICR*

Figure 5.2.06 *Outbred Mice: Female – HSD – ICR #2*

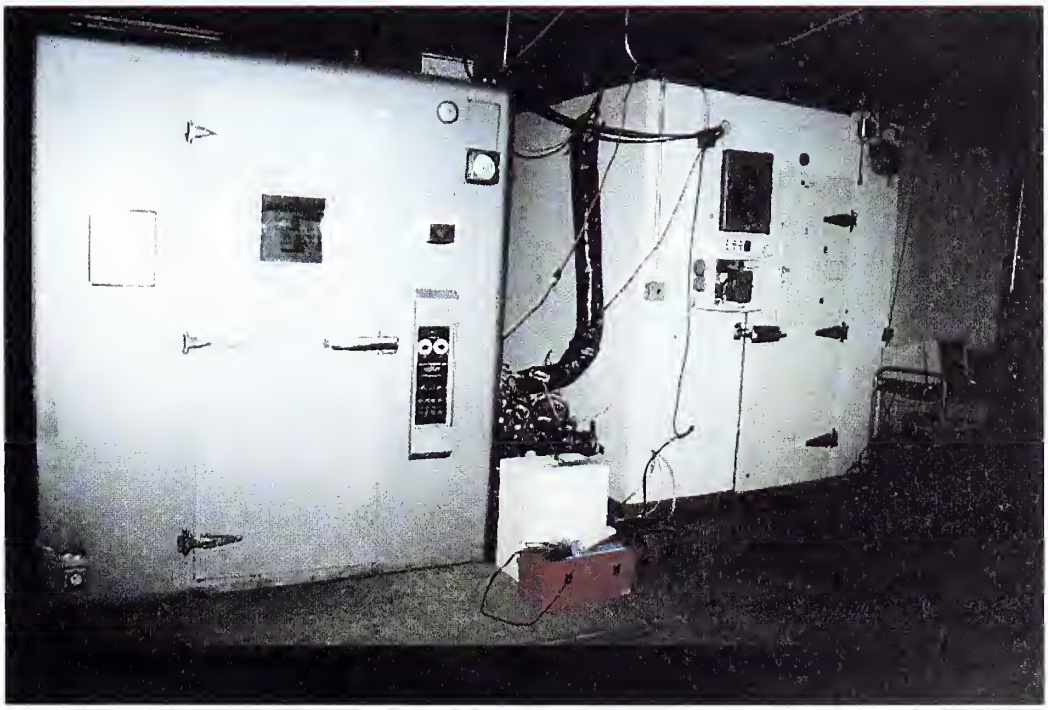


Figure 5.2.07 *Environmental Chamber Used for Housing Mice*

Figure 5.2.08 *Inside of Environmental Chamber*

5.3 Room Condition

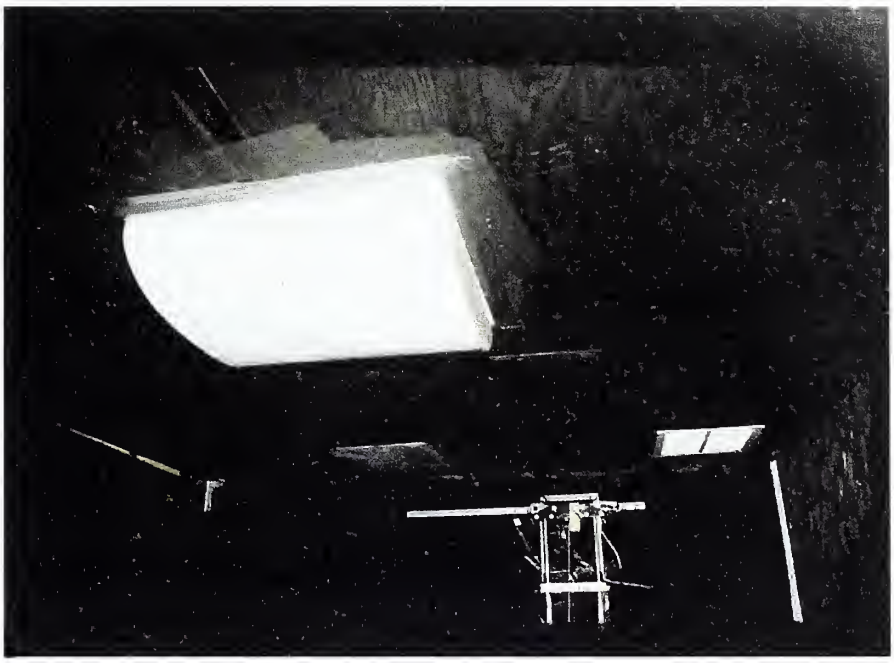


Figure 5.3.01 *Total Air Distribution (TAD) Diffuser, and Velocity and Temperature Measuring Sensors*

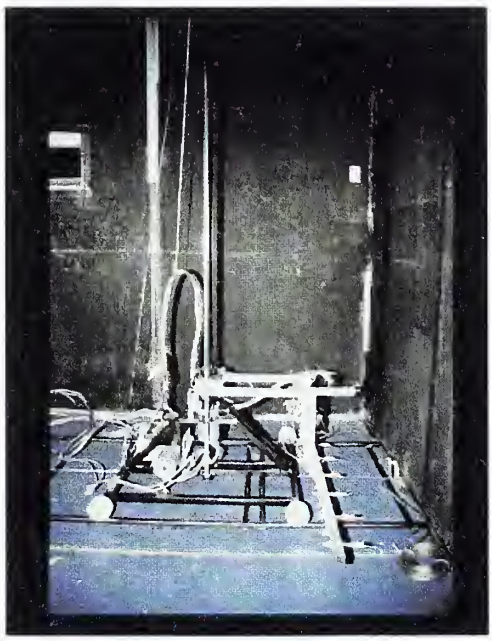


Figure 5.3.02 *Automatic Traverse System*

Figure 5.3.03 *Automatic Traverse System*

Figure 5.3.04 *Empty Room Data Collection*

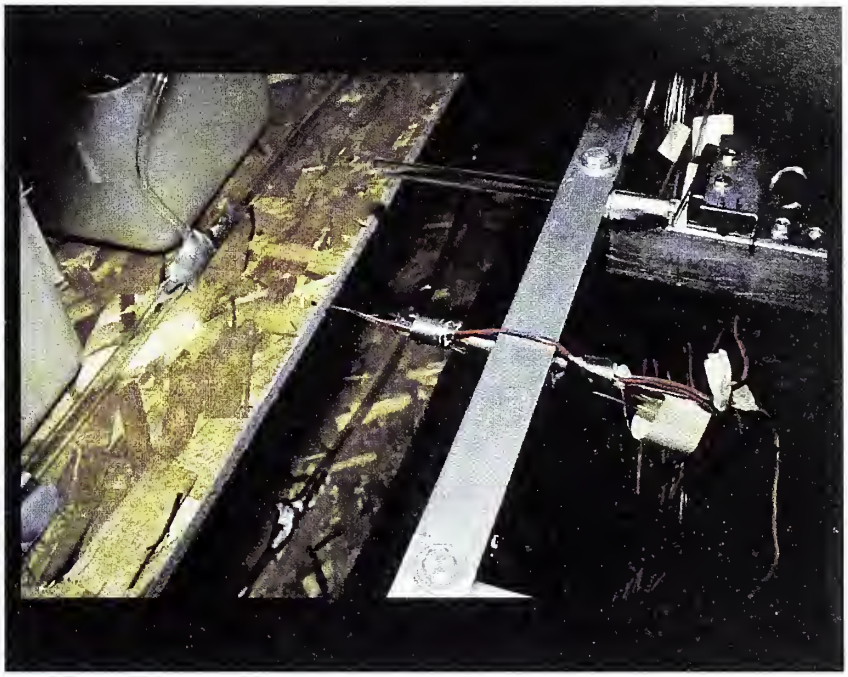


Figure 5.3.05 *Measurement Sensors for Populated Room*

Figure 5.3.06 *Typical Rack: Populated Room*

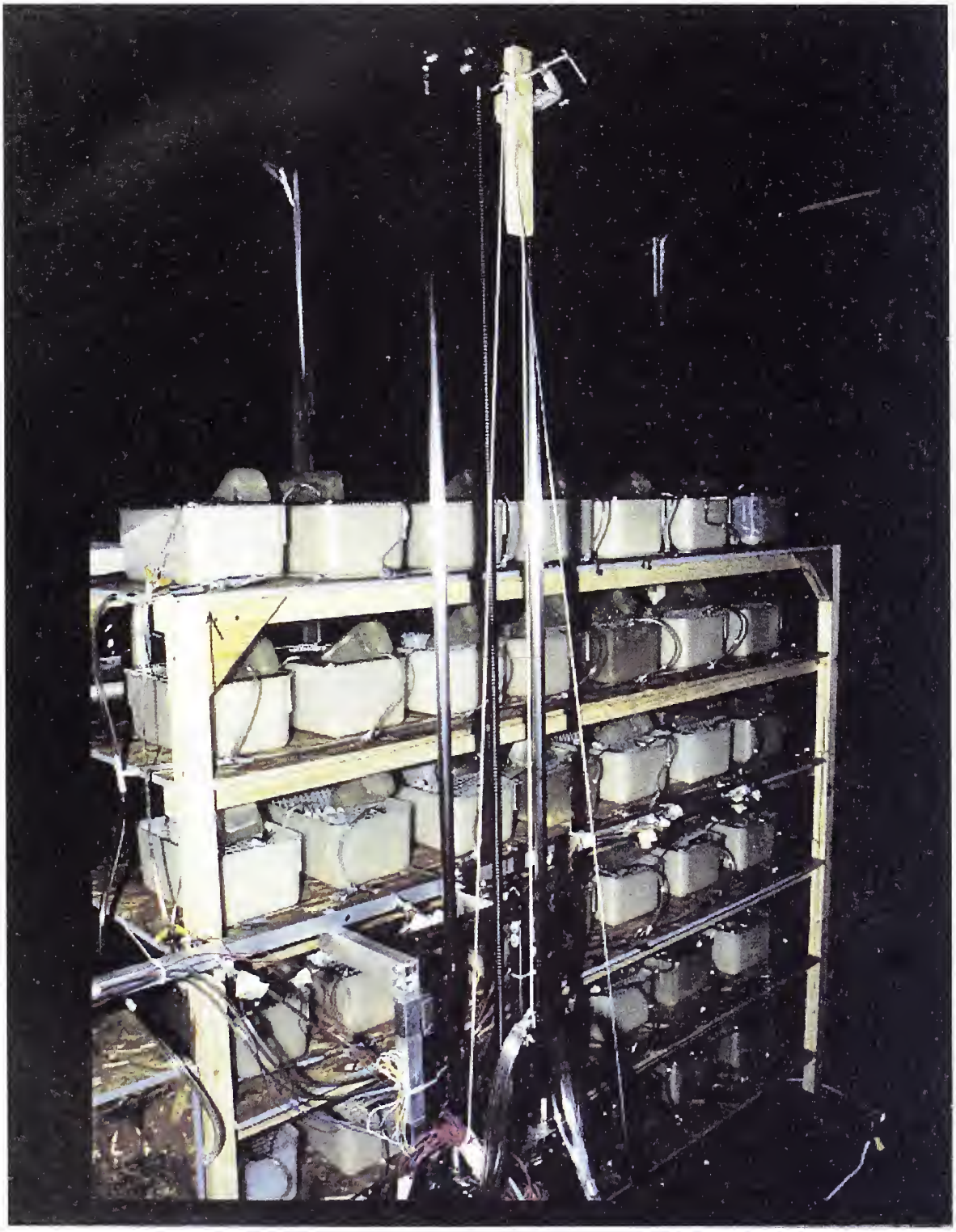


Figure 5.3.07 *Typical Rack: Populated Room #2*

Figure 5.3.08 *Typical Rack: Populated Room #3*

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